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## Watershed Management on Range and Forest Lands Proceedings of the Fifth Workshop of the United States/Australia Rangelands Panel

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**Edited by**

**Harold F. Heady  
Donna H. Falkenberg  
J. Paul Riley**

**Utah Water Research Laboratory  
College of Engineering  
Utah State University  
Logan, Utah**

**March 1976**

**UNITED STATES  
UNIVERSITY OF  
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**Harold F. Heady**  
Workshop Chairman

## PREFACE

### The U.S.-Australia Cooperative Rangeland Science Program

In October 1968 the governments of the United States and Australia entered into an agreement for the purpose of facilitating close cooperative activities between the scientific communities of the two countries. The joint communique issued at that time designated the U.S. National Science Foundation and the Australian Commonwealth Department of Education and Science as the coordinating agencies. Both countries were to encourage binational teamwork in research, interchanges of scientists, joint seminars, and exchanges of information.

A United States-Australia Rangelands Panel was established in December 1969 to further cooperation between the two countries in the rangeland sciences. The present panel includes the following:

<b>United States</b>	<b>Australia</b>
Dr. Harold F. Heady (Co-chairman) University of California	Mr. R. A. Perry (Co-chairman) CSIRO
Dr. James Blaisdell Forest Service	Professor R. O. Slatyer Australian National University
Dr. Thomas N. Shiflet Soil Conservation Service	Mr. E. J. Waring Bureau of Agricultural Economics

After the untimely death of the first U.S. Co-chairman, Dr. Kreitlow, in 1971, the U.S. membership was reconstituted. Mr. George Lea, Bureau of Land Management became Co-chairman. Dr. Harold F. Heady, University of California and Dr. Donald N. Hyder, Agricultural Research Service, replaced Dr. Kreitlow and Dr. Daniel Challinor, Smithsonian Institution. Following the third workshop in 1973, Dr. James Blaisdell, Forest Service replaced Mr. George Lea and Dr. Heady became the U.S. Co-chairman. In early 1975, Dr. Thomas N. Shiflet, Soil Conservation Service, replaced Dr. Hyder.

The Panel organized a series of binational workshops of about 30 scientists to examine selected subject matter areas in depth. The first meeting on "Plant Morphogenesis as the Basis for Scientific Management of Range Resources" was held in Berkeley, California March 29 to April 6, 1971. Eight Australian and eighteen United States scientists participated. The proceedings were published in U.S. Dept. Agr. Misc. Pub. 1271 (1974), which can be purchased from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402, \$2.30.

The second workshop on "The Impact of Herbivores on Arid and Semiarid Rangeland Ecosystems" was held in Adelaide, Australia, April 10-19, 1972. Ten United States and twenty-three Australian scientists took part in the discussions.

The third workshop on "Arid Shrublands" started with a field tour from Salt Lake City, Utah, to Tucson, Arizona, where the prepared papers were presented and discussed. Nine

Australian and twenty-one United States scientists attended. Proceedings may be purchased from the Society for Range Management, 2120 South Birch Street, Denver, Colorado 80222, \$3.00.

The fourth workshop on "Rangeland Ecosystem Evaluation and Management" was headquartered at Alice Springs in the center of Australia during April, 1974. Twelve scientists, land administrators, and extension officers from the United States and twenty-one from Australia took part in the workshop.

Panel members and workshop participants gratefully acknowledge support by the National Science Foundation, the Australian Commonwealth Department of Science, and several governmental agencies in both countries which made these workshops possible. This venture into international cooperation has directly benefitted 138 different persons in the first five workshops. Personal contacts, increased understanding of problems faced by other scientists, detailed analyses of subject matter areas, and trading of ideas help the attendees to do a better rangeland job. The publication of proceedings aims to make the subject matter reviews available to all persons interested in rangeland use.

Both Australia and the United States require large amounts of water for industrial, domestic, agricultural, and recreational uses. Water supplies which meet these demands flow from range and forest watersheds. Logging, mining, grazing and other land uses on those watersheds affect the yield and the quality of water. Watershed management concerns maximizing the yield of good water and the other benefits of water systems. In these proceedings, scientists and leaders in the fields of watershed hydrology and management, range management, and water resource planning review their work within the broad context of multiple rangeland use.

**Harold F. Heady,  
University of California**

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## **Session I**

# **Water Resources and Problems: Economic, Social, and Physical Aspects**

# Evaluation of Water Resources: Philosophical Basis and Conceptual Problems

R. J. McConnen\*

## INTRODUCTION

I've divided the paper into four sections. The first deals with the establishment of my philosophical basis for resource planning. I emphasize the *my*. Five years ago—certainly ten years ago—I wouldn't have bothered with this section. I could have assumed that "all reasonable men" would have agreed with me. I would have been wrong of course, but there seemed to be that general agreement that technological power should be used to develop resources for the benefit of man. However, much earlier people from Muir to Leopold warned about the crass application of such ideas. If we do agree, then being reasonable men—we must also agree that not all well meaning men do agree. Men's values influence their goals and objectives. Reasonable men can and do have different values. The second section deals with benefit-cost—the conventional wisdom. Benefit-cost analysis is a means of looking at social or societal problems not problems in science. The question dealt with is neither "what is?" nor "what can be?" but rather "what should be?" The third section deals with a conceptual case study involving land and water use. The fourth and final section has the title "Value Free Decision Making? or Gifford Pinchot vs. John Muir." It represents a brief statement of my disabusement—of the rational approach to the process of social decision making. While we must recognize that making decisions about resources is more difficult than it used to be, I take comfort from Thoreau's statement "This time—like all other times is probably the best of times if we know what to do with it."

## THREATS AND COUNTER-THREATS: THE PHILOSOPHICAL BASIS FOR RESOURCE PLANNING

The March 1967 issue of *Science*, contained a widely reprinted article by historian Lynn White, Jr., "The Historical Roots of our Ecological Crisis" (White, no date). I think the article contains the best verbalization I have seen of a serious threat to what I regard as the rational process of resource planning. I don't mean resource

planning and decision-making as they occur in practice all too often. I mean an idealized resource planning and decision-making process with a goal of using resources in such a way as to give the greatest satisfaction to man. Some would regard White's argument as merely a threat to the entrenched process of resource planning. One needs only to observe the reaction by many bureaucrats in once powerful agencies to realize it as at least this last kind of threat. I personally don't agree with Lynn White. But I believe that White's general proposition is even more important to understand now than it was eight years ago. You now know my bias. You can guess my objective. But I urge you not to regard White's proposition as merely a strawman.

I think I can best give the basic ideas contained in White's proposition by giving you several brief quotes—which you must, of course, recognize are out of context.

But, it was not until about four generations ago that Western Europe and North America arranged a marriage between science and technology, a union of the theoretical and the empirical approaches to our natural environment. The emergence in widespread practice of the Baconian creed that scientific knowledge means technological power over nature can scarcely be dated before about 1850, save in the chemical industries... (White, p. 14)

The quite sudden fusion of these two, towards the middle of the nineteenth century, is surely related to the slightly prior and contemporary democratic revolutions which, by reducing social barriers, tended to assert a functional unit of brain and hand. Our ecologic crisis is the product of an emerging, entirely novel, democratic culture. The issue is whether a democratized world can survive its own implications. Presumably we cannot unless we rethink our axioms. (White, p. 15)

Our daily habits of action, for example, are dominated by an implicit faith in perpetual progress which was unknown either to Greco-Roman antiquity or to the Orient. It is rooted in, and is indefensible apart from, Judeo-Christian teleology. The fact that Communists share it merely helps to show what can be demonstrated on many other grounds: that Marxism, like Islam, is a Judeo-Christian heresy. We continue

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today to life, as we have lived for about 1700 years, very largely in a context of Christian axioms. (White, p. 19)

However, the present increasing disruption of the global environment is the product of a dynamic technology and science which were originating in the Western medieval world against which Saint Francis was rebelling in so original a way. Their growth cannot be understood historically apart from distinctive attitudes toward nature which are deeply grounded in Christian dogma. The fact that most people do not think of these attitudes as Christian is irrelevant. No new set of basic values has been accepted in our society to displace those of Christianity. Hence we shall continue to have worsening ecologic crisis until we reject the Christian axiom that nature has no reason for existence save to serve man. (White, p. 25)

Both our present science and our present technology are so tinctured with orthodox Christian arrogance toward nature that no solution for our ecologic crisis can be expected from them alone. Since the roots of our trouble are so largely religious, the remedy must also be essentially religious, whether we call it that or not. We must rethink and refeel our nature and destiny. The profoundly religious, but heretical, sense of the primitive Franciscans for the spiritual autonomy of all parts of nature may point a direction. I propose Francis as a patron saint for ecologists. (White, p. 26)

My disagreement with White is not theological. White uses the term Christian to include what he calls post-Christian thought and its use is in a philosophical rather than religious sense. Rather than insisting that man act in the interest of other people and other living things, I think it is better to enable man to know more about how things influence his best interests. It's my contention that man can (must?) maintain his "faith in perpetual progress" and continue to contend, "that nature has no reason for existence save to serve man." But, to do this well, man must understand more in order to better understand what is in fact in his best interests. If we accept White's ideas, it would be far too easy to confuse intermediate means with ultimate goals. If man acts, I think he can only be expected to act in what he perceives to be his best interest. Man's perceptions may change. One purpose of education is to broaden man's perception of his best interest. Research results provide new information which certainly changes man's perception of what is in his best interests. Both the germ theory of disease and the environmental movements here caused such changes.

John Passmore is professor of philosophy at Australian National University, Canberra. I think his book deals very well with the type of challenge White makes. The book's title is, *Man's Responsibility for Nature: Ecological Problems and Western Traditions* (Passmore, 1974).

Passmore argues that Western civilization and culture, is much more diverse than—for example—White's

image of our guiding philosophy. For example, Darwin's man was part of, not apart from the rest of nature. White neglects to mention the golden rule.

The traditional moral teaching of the West, Christian or utilitarian, has always taught men, however, that they ought not so to act as to injure their neighbors. And we have now discovered that the disposal of wastes into sea or air, the destruction of ecosystems, the procreation of large families, the depletion of resources, constitute injury to our fellow-men, present and future. To that extent, conventional morality, without any supplementation whatsoever, suffices to justify our ecological concern, our demand for action against the polluter, the depleter of natural resources, the destroyer of species and wildernesses.

One of my colleagues, an ardent preservationist, condemns me as a 'human chauvinist'. What he means is that in my ethical arguments, I treat human interests as paramount. I do not apologize for that fact; an 'ethic dealing with man's relation to land and to the plants and animals growing on it' would not only be about the behavior of human beings, as is sufficiently obvious, but would have to be justified by reference to human interests. The land which a bad farmer allows to slip into a river did not have a 'right' to stay where it was. The supposition that anything but a human being has 'rights' is, or so I have suggested, quite untenable. (Passmore, 1974, p. 186-187)

Passmore believes in science as a means of achieving greater benefits for mankind, and has both praise and a warning. The first job however is to clear away what Locke called, ". . . some of the rubbish that lies in the way to knowledge." The first candidate is,

. . . the view that mysticism can save us, where technology cannot. Science and technology, democracy and free enterprise have always had their enemies; mysticism, primitivism, authoritarianism have always had their adherents. The ecologically-based protest—not only against shortsightedness and greed but, more fundamentally, against those attitudes to nature and society which are used to justify shortsightedness and greed—is, I have freely admitted, fully justified in itself. But it is being deployed as a new and powerful weapon in the old battle between rationality and mysticism. . . (Passmore, 1974, p. 173)

But the task we have now to undertake, in attempting to estimate the long-term effects of our actions both on the biosphere and on human societies, is so immense that in relation to it our ignorance is almost total.

To correct this situation may well require, I am fully prepared to admit, a minor revolution within science. The scientist will be forced, in the unenthusiastic words of one of my scientific colleagues, 'to slosh about in that primordial ooze known as interdisciplinary studies.' (Passmore, 1974, p. 177)

Passmore completes his book with the following:

What troubles me, however, is that it is hard to see any way in which the West can change its economic habits which does not entail the shifting of decisions about choices from the market to governments. This has already happened, of course, to a large degree; those income-earners—most of us—who have not learned the art of tax-evasion will have a large part, perhaps the greater part, of their income spent for them by the government. Whether this process can be carried further in a manner which does not entail the gradual emergence of a bureaucratic police state and the stifling of enterprise is, for me, the question of questions. Is Sweden, as has recently been argued, the prime example of creeping totalitarianism? (Passmore, 1974, p. 193-194)

What in general I have emphasised is that, if the world's ecological problems are to be solved at all, it can only be by that old-fashioned procedure, thoughtful action. We may, of course, think to no purpose; by acting thoughtfully we may make matters worse. As we know quite well in our personal lives, we are sometimes saved by rashness, destroyed by prudence. Looking before we leap may make cowards of us. But there is no alternative policy. Mystical contemplation will not clean our streams or feed our peoples, no invisible guiding hand, whether Providence or History, guarantees our salvation. In the biosphere, as I said, man has not tenure; his own folly may, at any time, lose him his precarious occupancy.

How and what we think, however, is determined not only by our brain structure but by the nature of the possibilities our society leaves open to us, the forms of thinking its traditions permit and encourage. The modern West, I have argued, leaves more options open than most other societies; its traditions, intellectual, political, moral, are complex, diversified and fruitfully discordant. That gives it the capacity to grow, to change: it nurtures within itself the seeds of innumerable revolutions. It is inventive—not only technologically, but politically, administratively, intellectually. Its flexibility gives it a better, not a lesser, chance of solving its problems. Admittedly, its central Stoic-Christian traditions are not favourable to the solution of its ecological problems—those traditions which deny that man's relationships with nature are governed by any moral principles and assign to nature the very minimum of independent life. But they, I have sought to show, are not the only Western traditions and their influence is steadily declining.

If, a century hence, men live worse lives than they do today, that will not be because the traditions of the West have bemused them; greed, ignorance, shortsightedness, fanaticism, are not Western inventions. How in fact they will live I have not dared to guess. My sole concern is that we should do nothing which will reduce their freedom of thought and action, whether by destroying the natural world which makes that freedom possible or the social traditions which

permit and encourage it. (Passmore, 1974, 194-195)

William Baxter, a lawyer, states a somewhat similar case in more popular language.

My criteria are oriented to people, not penguins. Damage to penguins, or sugar pines, or geological marvels is, without more, simply irrelevant. One must go further, by my criteria, and say: Penguins are important because people enjoy seeing them walk about rocks; and furthermore, the well-being of people would be less impaired by halting use of DDT than by giving up penguins. In short, my observations about environmental problems will be people-oriented, as are my criteria. I have no interest in preserving penguins for their own sake.

It may be said by way of objection to this position, that it is very selfish of people to act as if each person represented one unit of importance and nothing else was of any importance. It is undeniable selfish. Nevertheless I think it is the only tenable starting place for analysis for several reasons. First, no other position corresponds to the way most people really think and act—i.e., corresponds to reality.

Second, this attitude does not portend any massive destruction of nonhuman flora and fauna, for people depend on them in many obvious ways, and they will be preserved because and to the degree that humans do depend on them.

Third, what is good for humans is, in many respects, good for penguins and pine trees—clean air for example. So that humans are, in these respects, surrogates for plant and animal life.

Fourth, I do not know how we could administer any other system. Our decisions are either private or collective. Insofar as Mr. Jones is free to act privately, he may give such preferences as he wishes to other forms of life: he may feed birds in winter and do with less himself, and he may even decline to resist an advancing polar bear on the ground that the bear's appetite is more important than those portions of himself that the bear may choose to eat. In short my basic premise does not rule out private altruism to competing life-forms. It does rule out, however, Mr. Jones' inclination to feed Mr. Smith to the bear, however hungry the bear, however despicable Mr. Smith.

Insofar as we act collectively on the other hand, only humans can be afforded an opportunity to participate in the collective decisions. Penguins cannot vote now and are unlikely subjects for the franchise—pine trees more unlikely still. Again each individual is free to cast his vote so as to benefit sugar pines if that is his inclination. But many of the more extreme assertions that one hears from some conservationists amount to tacit assertions that they are specially appointed representatives of sugar pines, and hence that their preference should be weighted more heavily than the preferences of other humans,

who do not enjoy equal rapport with "nature." The simplistic assertion that agricultural use of DDT must stop at once because it is harmful to penguins is of that type.

Fifth, if polar bears or pine trees or penguins, like men, are to be regarded as ends rather than means, if they are to count in our calculus of social organisation, someone must tell me how much each one counts, and someone must tell me how these life-forms are to be permitted to express their preferences, for I do not know either answer. If the answer is that certain people are to hold their proxies, then I want to know how those proxy-holders are to be selected: self-appointment does not seem workable to me. (Baxter, 1974, p. 5-7)

It is comforting to an economist to read such words. While Baxter has ". . . no interest in preserving penguins for their own sake," it may be (and probably is) very important to establish the objective of preserving penguins as a means to enhance the well being of people. But whether or not this is the case should be determined as the result of thoughtful action, not blind faith.

#### BENEFIT-COST ANALYSIS—THE CONVENTIONAL WISDOM

In this section, I want to look at three things. First, I want to look at the conceptual framework for benefit-cost analysis. Second, I will briefly mention the problems associated with sub-optimization. Third, I want to point out the obvious: the question "Who gets what—and for whom?" must be dealt with. Economists have little to say in an analytical sense about the question "Who gets what—and from whom?" This is unfortunate for two reasons. First, no other discipline has anything more to offer. Second, if we are to evaluate water resources, the evaluation must be based on the comparison of alternatives. A complete comparison requires the question be answered.

Benefit-cost analysis is based on a comparison of alternatives. One alternative is to do nothing. If nothing is done, it does not follow that nothing will happen. For

example, the geological process did not await the arrival of man. In some cases, man's activities have accelerated that process. In some cases, the do nothing alternative may mean a continuation of farming activities which have speeded up the geological process, i.e., there is a net addition to the "natural" sediment load of a stream as the result of a farming practice. So to do nothing—or rather nothing different—is always an alternative that must be considered.

The meaning of benefit is clear in a primitive sense. In a technical operational sense, the mean of benefit can be—and usually is—the source of a good deal of difficulty. The primitive meaning of cost is likewise fairly easy to grasp, but for some reason, its meaning is often confused. Costs are merely benefits that have to be given up. For example, assume one alternative is to build a dam which will flood an agricultural valley. If society selects that alternative, it will have given up some benefits it would otherwise have received. Society will no longer be able to get the benefits from using the labor, energy, concrete, and steel needed to build the dam to do other things which would have benefited society. In addition, it will no longer be able to receive the benefits from agricultural land, recreational use of the river, etc. The expression of costs in dollar terms is an attempt to find a single numerare for the aggregate value of costs for many different types of benefits that will have to be given up if this particular dam is built. Cost is an abstract concept built on the very real basis of benefits given up.

Alternative X is better than alternative Y if the social benefits are greater than the social costs. To state it another way, "Alternative X is better than Alternative Y if the benefits we gain from X will be greater than the benefits we give up by not choosing Y." Simple enough, but of course there are complications. There always are.

One significant complication relates to the question of divisibility of alternatives. The problem is outlined by using a simple example—adopted from Mishan (1973, p. 134). Table 1 contains the benefits (B) and costs (C, i.e., benefits foregone) for two alternatives I and II. Which is the best alternative?

**Table 1. Benefit-cost analysis and the problem of divisibility.**

Alternative	Benefit B	Cost C	Benefit-Cost B-C	Benefit/Cost Ratio B/C
I	150	100	50	1.5
II	50	20	30	2.5

Case 1. Alternative II cannot be duplicated, alternative I is an all or nothing proposition, and 100 units of cost are available. In this case, I is the best alternative even though its B/C ratio is only 60 percent of the B/C ratio for II.

Case 2. I is divisible, II cannot be duplicated and costs can be as great as 100 units. In this case, II should be selected plus 80 percent of I. Benefits less costs will be  $30 + (0.8)(50)$  or 70.

Case 3. II can be duplicated, costs can be as great as 100 units, and the restrictions on I are of no concern. II should be duplicated five times and total benefits less costs will be 150 units.

These are simple examples. But the obvious is still obvious. Benefit-cost analysis must involve more than calculating benefit-cost ratios. To stop there is to practice a black bureaucratic art. It is not benefit-cost analysis. In order to engage in benefit-cost analysis, the full range of feasible alternatives must be considered.

Benefits and costs can and do occur at different points in time. For many reasons, a dollar in 1980 is not the same as a dollar in 1975. A common procedure used to deal with this difficulty is to express all values in terms of present values.

Present value of benefit and costs means discounting. That requires the use of interest rates. The Rule of 70 works here too. Divide 70 by the interest rate—say 7 percent. With an interest rate of 7 percent a dollar earned 10 years from now has a present value of about 50 cents. When future benefits and costs are discounted to present value, the future is given less weight than the present. And discounting can significantly change the relative net social value of alternatives.

But why discount? Baxter puts it this way:

In a society that functions at bare survival levels, the feasibility of delaying the consumption that corresponds to one's current productive activities is sharply limited; the supply of credit, or capital, will be small and interest rates will be relatively high. In a more affluent society there are a larger number of persons around who are in a position to consume less than all they are entitled to consume at any particular point in time, and interest rates characteristically will be relatively lower. Obviously there are other factors that affect the level of interest rates, and my suggested generalization that interest rates will be higher in less affluent societies is overbroad; but the point has a basic validity, and it focuses sharply on what interest rates really are. They are the rewards one receives for permitting someone else to consume presently what the lender is entitled to consume on the basis of his own consumption and transferring to others entitlement to present consumption is a very real service, and it is for this service that, interest payments are made. (Baxter, 1974, p. 22)

Interest costs are opportunity costs. A reflection of the first law of political economy, TANSTAAFL (There Ain't No Such Thing As A Free Lunch). This is easily understood on a personal basis.

Interest rates represent the cost of waiting. Why should society use interest rates in evaluating alternatives? Presumably because societies also have limited resources. Those resources must be allocated—hopefully rationally. This involves the question of *how and for what* should they be used and *when* should they be used. Failure to discount future benefits and costs is equivalent to using a zero interest rate. This may be appropriate, but that decision should be made explicitly not implicitly.

Nobody... holds, 'writes Pigou,' that the State should force its citizens to act as though 'so much objective wealth now and in the future were of exactly equal importance.' In view of the uncertainty of productive developments, to say nothing of the morality of nations and eventually of the human race itself, this would not, even in extremest theory, be sound policy. But there is wide agreement that the State should protect the interests of the future in some degree against the effects of our irrational discounting and of our preference for ourselves over our descendants. And certainly, the state's own future may well depend on the extent to which it can persuade its citizens to conserve resources. Unlike individual human beings, it looks forward to a life of indefinite length; there is no equivalent, in the history of a state, to 'three score years and ten'.

At the same time, the state is not an impartial entity, making its decisions with a wisdom and sureness to which its citizens cannot possibly aspire. In fact, no state can be as wise as the wisest of its citizens; it is subject to, and must in some measure allow for, the pressures from the most foolish. Its own discounting may easily be 'irrational', as it seeks votes from supporters whose only concern is to maximize present gains. Quite contrary to Pigou, C. P. Snow suggests, indeed, that 'it is in the nature of politics that the short-term duties come first.' (Passmore, 1974, p. 95)

Benefit-cost analysis for public purposes is concerned with maximizing social benefits in excess of social costs. But which society? Is the society Boise County, Idaho, Australia with a 3.5 percent population growth, or Australia with a 2 percent population growth? There is no right answer, but it is a right question that must be answered for each analysis. The way in which it is answered can have a great impact on your conclusions. For example, the B/C ratio (associated with a proposed dam) may be favorable for the community of Down Valley, but very unfavorable if the community is defined as Down Valley *plus* Upper Valley which is a heavily used recreation area by the people from Big City.

Kenneth Boulding has stated, "I have found the name of the Devil and this is an important discovery. The name of the Devil is sub-optimization." And yet, we sub-optimize in terms of time, and in terms of how we perceive the boundaries of a society. If we are to reach a decision, we reach a point where we say, "This counts—that doesn't." Necessary. But we should remember, our boundary is probably largely based on expediency—not ultimate wisdom.

Mishan states, "But the quantitative outcome of a cost-benefit calculation itself carries no distributional weight, it shows that...the economist can... say something about the distribution resulting from the introduction of an otherwise feasible project." (Mishan, 1973, p. 16.) Mishan feels—and I agree—the economist can do little more. In fact, he should be wary of the temptation

to do more than point out the tradeoffs between efficiency and equity. We might feel more comfortable if we were able to accomplish the impossible and quantify a total utility of social welfare function. But again, as Mishan points out, "...the resulting utility—weighted cost-benefit criterion could still admit projects (or policies) that make the rich richer and the poor poorer. . ." (Mishan, 1973, p. 24). Regardless of how we view "distributional dimensions," in terms of either people or sectors, I think the economist can make the greatest contribution with regards to this problem when he functions in a positive rather than a normative framework. Obviously, the "who gets what" question is fundamental as a normative question. Therefore, it is also fundamental as a positive question. In so far as reasonable, we need estimates of distribution of both costs and benefits if we are to properly evaluate the use of water resources. This is far too little to say about the explosive question of income distribution. Yet, except for an elaboration of some descriptive tools, there is little to be added except for (1) additional discussion about why it's important to consider income distribution and (2) why you should be for the type of income distribution that is based on my values. In my view, neither is productive ground for further exploration at this time.

In most cases, benefit-cost analysis is used to deal with complex social problems. The purpose is to select that alternative or set of alternatives which will result in the greatest excess of social benefits over social cost. In an operational sense, this involves great difficulties. Some of the conceptual problems have been mentioned briefly above. Only a few of the operational problems will be explored below.

#### LAND AND WATER USE: A SIMPLIFIED CASE STUDY

This particular case study involves a high degree of abstraction. The problems mentioned above; divisibility, discounting to adjust for time, and income distribution, are not dealt with in this case study. There is one additional basic conceptual problem which is not dealt with which is part and parcel of almost all resource problems. This problem relates to the stochastic and the sequential nature of almost all resource systems. Picasso has said, "All art is a lie that lets us understand the truth." And of course, so are all models. Models are a simplification of reality which helps us to understand the truth—hopefully. A model concentrates on certain elements and does not explicitly consider other elements. What to include and what to exclude is a matter of judgment which is greatly influenced by the purpose of the modeling effort.

The purpose of presenting this case study is to illustrate five ideas that should be used in developing models to be used in evaluating resources. The five ideas are presented in a linear fashion but the process in which they're used should be continuous and involve feedback.

First, an inventory of relevant resources must be obtained. Second, a set of goals or objectives must be specified. In this case study, one of those goals will be used as an objective function. Third, alternative courses of action must be defined. Fourth, the linkage between each resource and each goal must be specified for each alternative. In some cases, there will be no linkage, but this must be established explicitly. Fifth, the initial simple model must be developed in each a way so that the model can be expanded as the analyst's understanding of the resource system being studied increases.

As discussed in the first section of this paper, the ultimate goals must be in terms of benefit to human beings. In operational models, this is sometimes difficult to do and intermediate means of achieving the ultimate goals are often used as proxies for the ultimate goals. For example while the ultimate goal may be maximum social well being, the operational goal may be expressed in terms of maintaining air of a particular quality. While such things may be a necessary abstraction, it's imperative that the analyst remember the nature of the abstraction. It's critical that the means—air quality—be remembered as that and not be mistaken for the ultimate goal—maximum social welfare. In many cases, the ultimate goals can only be achieved by relaxing the initial specifications for the proxies which have been developed for the ultimate goal. To take an extreme example, in order to achieve the air quality initially specified, it may be necessary to eliminate activities which contribute a great deal to social well-being. Obviously, it would be a serious mistake to mistake a crude proxy—air quality—for the ultimate goal—social well-being. This is why most analysis of socially relevant problems can at best provide the final decision maker with information the decision maker will find of value. It's particularly important to keep in mind the relationships between specified goals and ultimate goals. In only rare cases, can the analysts provide the "best" answer in place of "good information."

The case study will involve multiple-use land management (with one of the products being water) and the multiple-use management of a water storage facility (McConnen, no date). The multiple-use land management problem is outlined in schematic linear programming form in Figure 1. The amount of each resource available is inventoried as Class 1 through Class n. There are six operational goals. The system must be operated so at least a certain amount of water, timber growth, etc. are produced. One of the goals is to limit net budget cost and this has been specified as the objective function which is to be minimized. Another way of handling the multiple goals would have been to specify an upper limit for net budget costs and operate the system with maximization of water production as the objective function. Once the resource inventory, goals (including the objective function) have been specified, the third step is to specify the alternatives (treatments or manipulation activities) which will be considered. The fourth step is to link each resource to each



goal for each alternative. For example, if an acre of Class 1 land is clear cut, the impact on each of the six goals must be specified in the product mix sector and on the objective function.

How is the model to be used? The first step is to see if in fact it is feasible to achieve the specified goals given the resource base and the alternatives that have been specified. In this sense, the model provides a test for the physical and biological feasibility of the problem. If the problem has no feasible solution, either the model and coefficients may have been incorrectly specified or the goals may be too ambitious for the existing resource base. Assume however that an initial optimum solution can be found. In most such cases, we know relatively little about the desirability of alternative combinations of values for goals. One approach would be to specify alternative sets of levels for the goal constraints and solve the problem again. Figure 2 presents the results for an Arizona watershed when the goal for total water produced was systematically changed. If the system is operated inefficiently the cost of producing a given amount of water can lie above the cost line in Figure 2. However, given the model specification, it is not feasible to produce a given amount of water at a cost less than that on the cost curve in Figure 2.

What is the optimum amount of water to produce? That depends on its value which depends in turn, on how it's used. Assume that the model in Figure 1 is constructed as a three time interval (spring, summer, and winter) model and that the water output enters the system outlined in Figure 3 at gaging station 1.

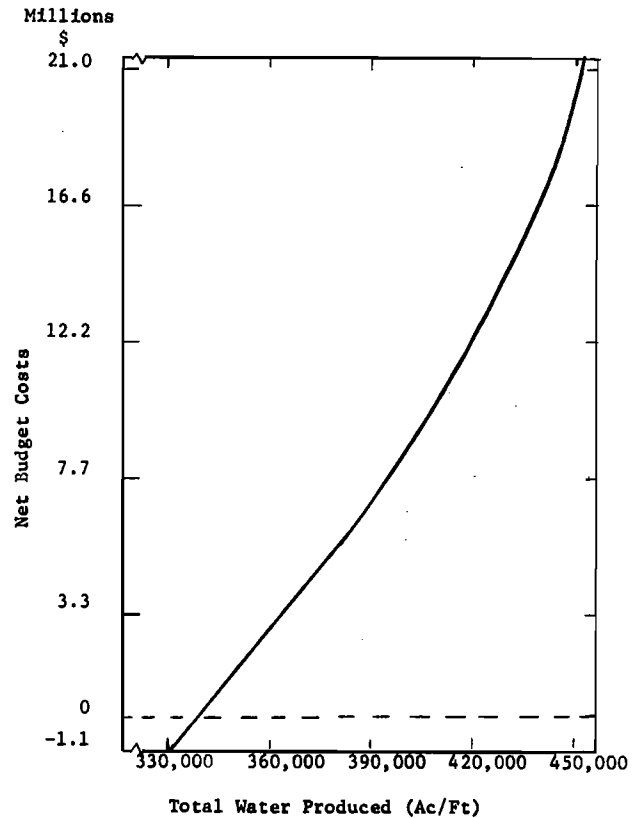


Figure 2. Relationship between net budget cost and total water produced.

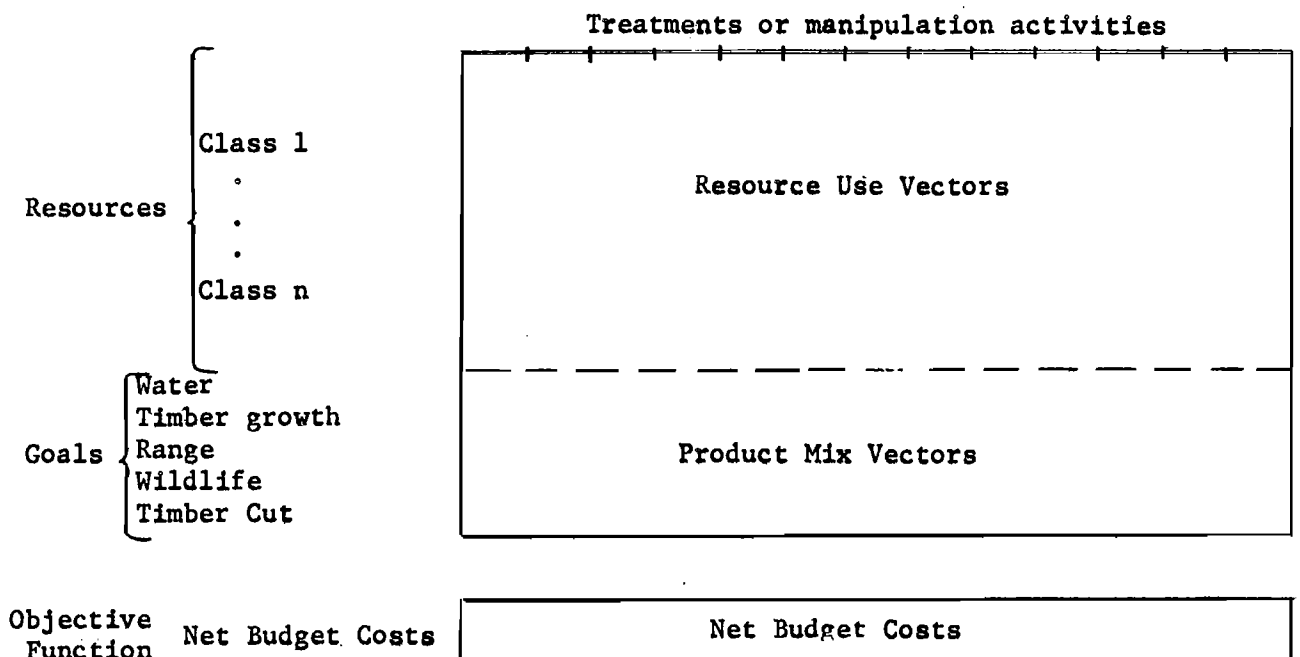


Figure 1. Stable state multiple use model.

The purpose is to operate the existing water development in order to maximize social well being. The way in which the system is operated will influence (1) satisfaction from using summer homes, (2) lake fishing, (3) boating, (4) irrigated agriculture, (5) power production, and (6) river fishing. These are means of achieving the ultimate goal—social well-being. The degree to which these intermediate goals (means) can be achieved will be influenced by the lake level and river flow for different time intervals. For example, it is assumed that summer home use will occur only in the summer and the exposure

of mud flats in front of the summer homes will be of no concern during spring (interval 1) and winter (interval 3).

The problem in Figure 3 is presented as a linear programming problem in Figure 4. The descriptions of the variables for the three time interval model are presented in the footnote to Figure 4. The process of developing this model is basically the same as for Figure 1. For example, the coefficients  $b_1$ ,  $b_2$ , and  $b_3$  are equivalent to the coefficients of the product mix vectors on Figure 1. The model in Figure 4 is complicated by the need to tie the three intervals together into a single system.

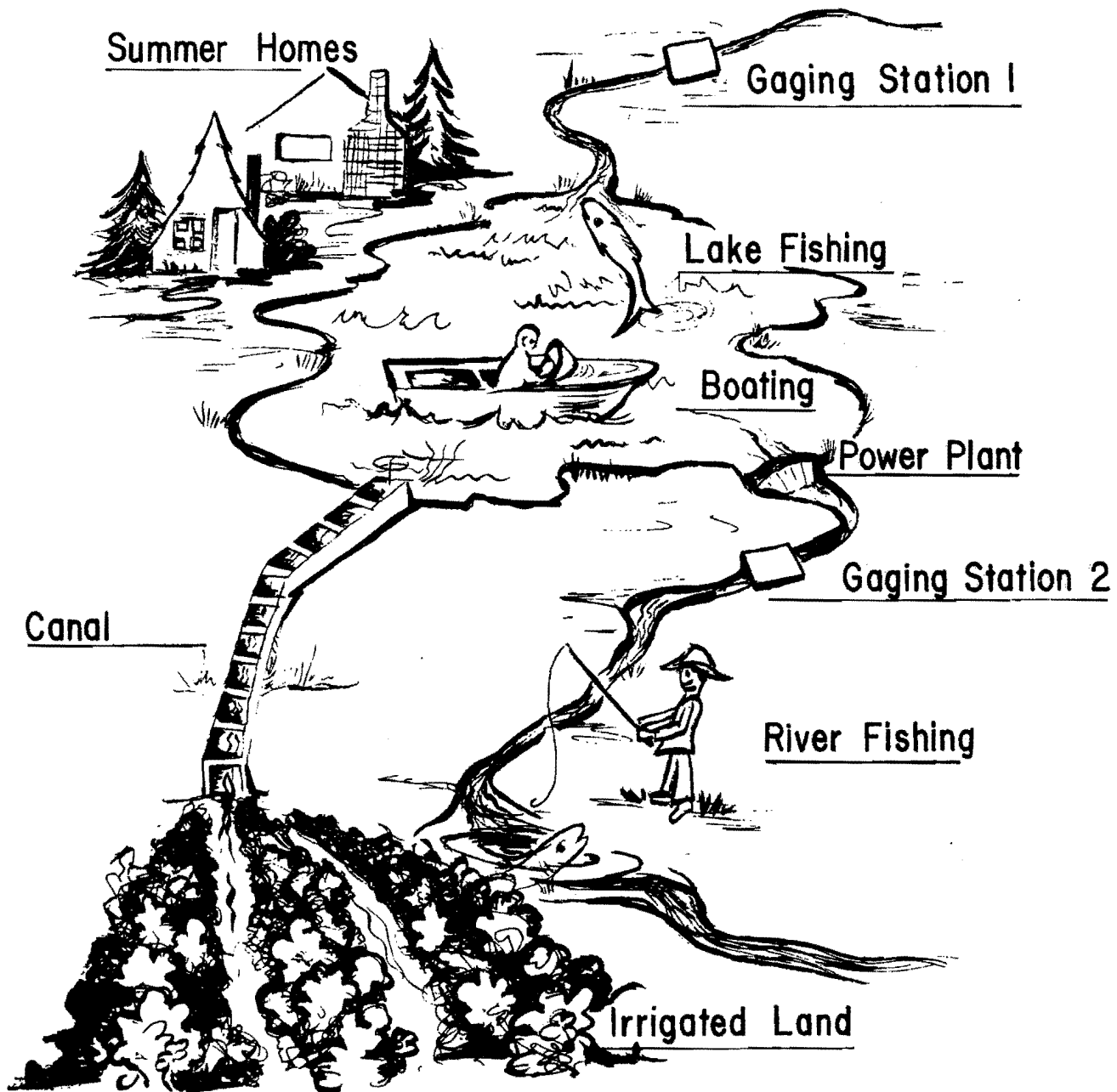


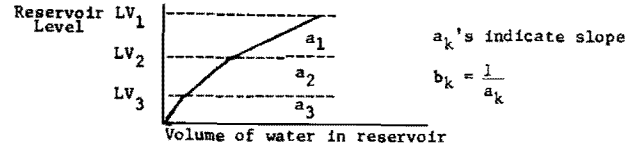
Figure 3. Schematic of multiple purpose water development.

NOTES ON FIGURE:

1. Variables names.

- $V_i$ : Volume in reservoir at the beginning of interval  $i$ .
- $F_i$ : Total volume of flow in interval  $i$  at gaging station 1.
- $I_i$ : Total volume of irrigation water for interval  $i$ .
- $P_i$ : Total volume of water for power production in interval  $i$ .
- $H_i$ : Level of reservoir required.
  - $H_1$ : Protection of reservoir fish habitat in interval 1.
  - $H_2$ : Protection of reservoir fish habitat in interval 2.
  - $H_3$ : Protection of reservoir fish habitat in interval 3.
  - $H_4$ : Required for a specified area of water for summer boating.
  - $H_5$ : Required to cover mud flats in front of summer home area.
- $K_i$ : Total volume of water at gaging station 2 in interval  $i$  required to maintain river fish habitat.

- $S_i$ : Total water released from spillway and gates in interval  $i$
- $T_{ik}$ : Variables which permit transfer of unused reservoir water from interval  $i$  interval and are used to specify the level of the lake.
- $LV_k$ : Indicates that the relationship between the reservoir level and volume of water in the reservoir is specified by the  $k$ 'th segment of the relationship below.



2. Disposal and slack activities have not been specified.

Constraints and Goals	$V_1$	$T_{3,1}$	$T_{3,2}$	$T_{3,3}$	$S_3$	$P_3$	$F_3$	$T_{2,1}$	$T_{2,2}$	$T_{2,3}$	$S_2$	$P_2$	$I_2$	$F_2$	$T_{1,1}$	$T_{1,2}$	$T_{1,3}$	$S_1$	$P_1$	$I_1$	$F_1$	$V_1$		
$V_1 =$	b/																						1	
$F_1 =$																								1
$0 =$																								1
Goals for Spring Interval																								1
$I_1 <$																								1
$P_1 <$																								1
$H_1 <$																								1
$K_1 <$																								1
$LV_3 =$																								1
$LV_2 =$																								1
$LV_1 >$																								1
$0 =$																								1
Goals for Summer Interval																								1
$F_2 =$																								1
$I_2 =$																								1
$P_2 <$																								1
$H_2 <$																								1
$H_4 <$																								1
$H_5 <$																								1
$K_2 <$																								1
$LV_3 =$																								1
$LV_2 =$																								1
$LV_1 >$																								1
$0 =$																								1
Goals for Fall and Winter Interval																								1
$F_3 =$																								1
$P_3 <$																								1
$H_3 <$																								1
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$LV_3 =$																								1
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$0 =$																								1
MAX Z																								
a/																								
b/																								

a/ Objective function is max, receipts from sale of irrigation water and electrical power.

b/ Provides a measure of the volume left in the reservoir at the end of 3rd interval.

Figure 4. A linear programming model based on Figure 3.

A modified Figure 1 (with three intervals) could be incorporated with the model in Figure 4 and the combined model could be operated as a single system—which in fact it is. The degree to which such elaboration is desirable will depend on things as disparate as computational capacity and assigned responsibilities.

This is a simple case study and it ends with no answers. Instead, it ends with a few preachments that are obvious but I think important enough to repeat for anyone involved in evaluating water resources.

First, we must know what our resources are. The inventory must be developed with recognition of both the goals and the alternatives which will be considered.

Second, we must know what we want to achieve—our goals. The goals must either be stated in operational terms or operational proxies must be developed.

Third, we have to specify which alternatives we will consider. Two elaborations should be made here. (a) To be evaluated, alternatives have to be specified. (b) One of the places an analyst can be constructively creative is during the process of developing acceptable alternatives. It is important, however, to keep the activities of evaluating and creating alternatives as separate as possible.

Fourth, for every alternative, we need the best objective information for relating resources and goals. Two elaborations should be made here. (a) It is seldom desirable to specify a goal in a particular way because we already have the data available. It is highly desirable, however, to use knowledge about goals as a mean of suggesting the kind of data we should try to gather. Therefore, goals should be specified before data are collected. (b) Theories are important sources of information, but whenever possible, empirical information related to the problem at hand should be used. It is too easy to forget the tentative nature of what may prove to be critical relationships hidden deep within an elaborate model.

Fifth, any model is a simplification. As we learn more, the predictive powers of a model can be improved. Still, at best a model is a simplification. Decision making will probably always involve an element of art. This is not only true because of our limited knowledge about biological and physical relationships. It is particularly true because of our limited ability to specify goals in terms that are fundamental and lasting.

#### **VALUE FREE DECISION MAKING? OR GIFFORD PINCHOT VS. JOHN MUIR**

Gifford Pinchot and John Muir are two of the giants in the American conservation movement. At one time, the men were close friends, but later, differences in their basic philosophies led to personal differences. Steward Udall described the basis for the difference as follows.

On the one hand, Pinchot looked on the public lands as a workshop to be managed for many

purposes under a plan of balanced use. Muir accorded a place in the resource picture to livestock and hydroelectric power but he gave first priority to preserving the finest landscapes of the public domain as temples unspoiled and intact. Drawing a line between the workshop and the temple was, and still is today, the most sensitive assignment for conservation planners. (Udall, 1963, p. 132)

Gifford Pinchot's model of conservation was based on "wise use" of resources. Pinchot's ideas were closely allied with the classical efficiency model. John Muir's ideas were part of the transcendental tradition. (McConnen, 1967, p. 7.) I expect John Muir would have endorsed Lynn White's ideas referred to earlier in this paper.

The ideas presented in this paper fall largely within the Pinchot school. But there is a major difference. An ardent follower of the Pinchot school—at least fifty years ago—would have no qualms about specifying the type of resource related goals presented in the case study above. The well trained resource scientist was to have few questions about what was good and what was bad with regards to resources. He knew! It's comforting to know you're right beyond any reasonable doubt. Few people working in resources today have that comfortable feeling. To be "right" in such circumstances is often little more than an implicit attempt to impose your (or my) values on others. The fact that such attempts may be presented as "scientific findings" is of less and less value. The followers of John Muir are alive, well, and living nearly everywhere. The process of decision making in the area of natural resources has changed. Social decisions are not value free. They shouldn't be and they cannot be. Evaluation of water resources is not equivalent to decision making. For the technical analysts, evaluation has come to mean analyzing and then presenting information in a form that can be used in a productive way by decision-makers in both the public and private sectors.

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# Water Resource and Land Use Problems in Western Australia

B. S. Sadler\*

## PART 1—STATE PERSPECTIVE

### Western Australia—The Land, Its Use and Social Background

#### *Size and relief*

The State of Western Australia is one-third of the Australian continent. In area, it covers 2.5 million square kilometers which is an area greater than the eight Mountain States of the USA from Montana to Arizona and New Mexico. In distance from north to south, it measures some 2300 kilometers or nearly 20 percent more than the distance from the Canadian to the Mexican borders.

More than 90 percent of the land area of the state and the whole of its interior is occupied by the Great Plateau (Figure 2), the major part of which is only 300 to 350 meters above sea level and the highest point of which is only 1250 meters above sea level. A large part of the interior of the plateau is riverless.

The western and north-western segments of the state are bordered by a narrow, almost continuous, low-lying coastal plain. The south-west section of this plain, the Perth Coastal Plain, supports 75 percent of the state population.

#### *Climate*

In latitude, the state ranges from approximately 14°S to 35°S. Its climate varies from a sub-tropical summer monsoonal situation in the north to a winter rainfall temperate climate in the south. In its mid latitudes and over the whole of its interior, the state has an arid or semi-arid climate (Figure 1).

Highest median annual rainfalls of around 1200 mm occur near the coast in the wettest parts of the south-west, but only small portions of the state in the extreme north and the south-west enjoy a median annual rainfall of 600 mm or more. For the greater part of the state, the median

annual rainfall is less than 400 mm and in the interior as low as 150 mm.

#### *Land use*

An area of slightly more than one million square kilometers or 40.4 percent of the state is Crown Land (land belonging to the state) leased almost entirely as large pastoral properties of natural grazing land. A further 36.5 percent of the state is unallocated Crown Land and because of its aridity and infertility, is of no use, on present knowledge, for agriculture, or grazing. Land holdings of the federal government are insignificant in Western Australia as in other States of Australia.

Approximately 195,000 square kilometers or 7.7 percent of the state has been released or is on conditional purchase from the state mostly for agricultural purposes. A large part of this area, the south west hinterland (Figure 3), is devoted primarily to cereal crops mixed with sheep and cattle production and is of major importance to the state's economy. Irrigated agriculture occurs on a relatively small area of freehold land on the Perth Coastal Plain and also in the far north.

Finally, an area of 390,000 square kilometers or 15.4 percent of the state is allocated to roads and reserves. Of this, a very small area of approximately 19,000 square kilometers or less than 0.8 percent of the state, is dedicated forest or timber reserves.

#### *Mineral resources and development policies*

The West Australian economy has traditionally been based on primary production, particularly from the agricultural, pastoral and mining industries. Secondary industry flowing on from the mining industry is of growing importance.

An area of substantial mineral wealth, the state has experienced early and recent mineral booms which have figured highly in its development history. At the present time large tonnages of high grade iron ore are being produced from the development of vast deposits in the arid Pilbara Region of the north-west. Major nickel fields are

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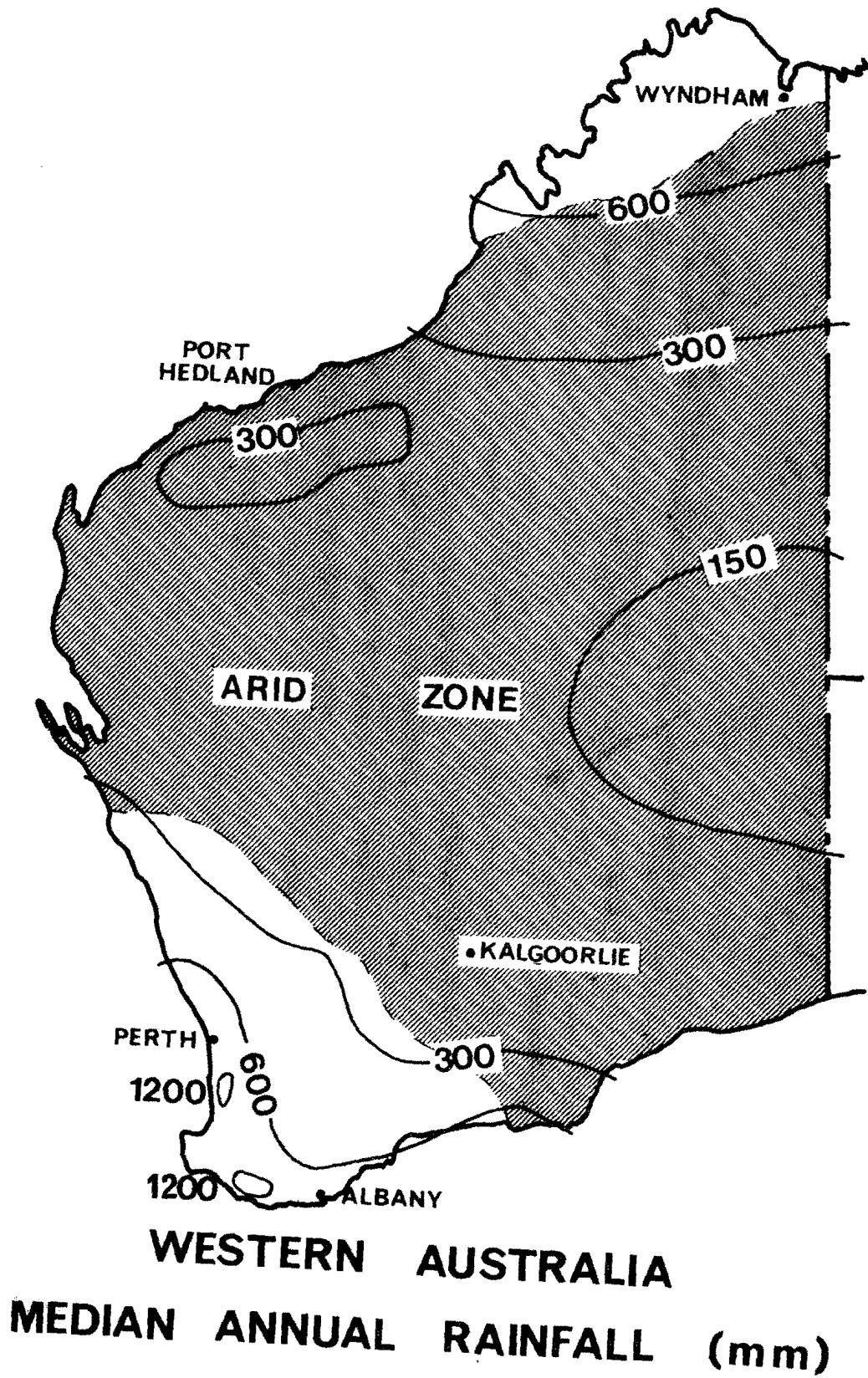


Figure 1.

# PRINCIPAL USEABLE POTABLE WATER RESOURCES OF WESTERN AUSTRALIA

$m^3 \times 10^6 / \text{ANNUM}$

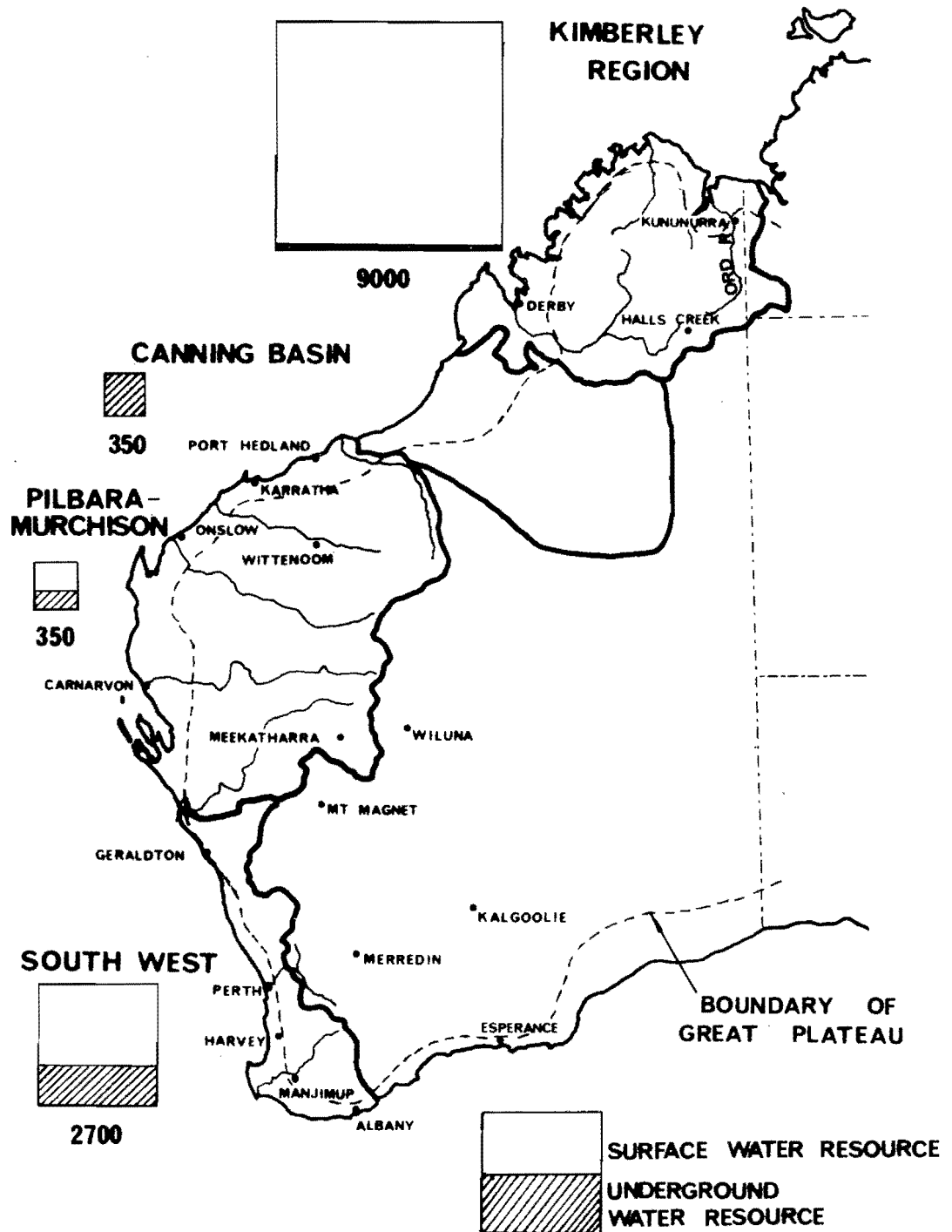
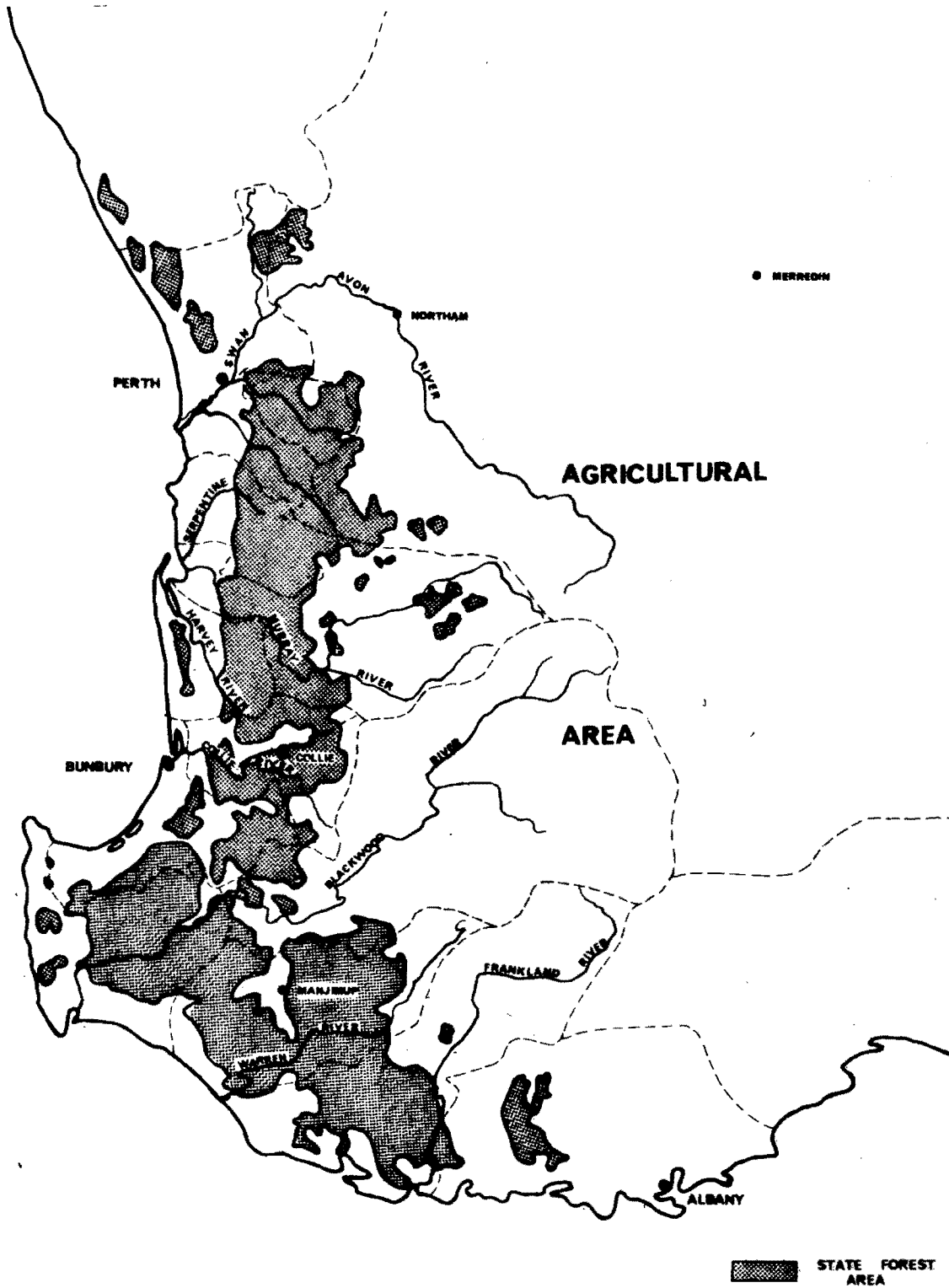


Figure 2.



**SOUTH WEST REGION  
FOREST AND AGRICULTURAL AREAS**

Figure 3.



being developed in former goldfields areas some 500 km inland in the southern half of the state. Bauxite is being profitably mined in the forests of the south-west and also occurs in the far north. Natural gas discoveries of useful magnitude have been made off shore from the Pilbara Region.

Large scale mineral developments which have occurred since the mid 1960's have added substantially to the nation's export income. The developments have been spurred by vigorous growth objectives of successive state governments each fostering the image of a "State on the Move." The use of land has been actively encouraged as one means of contributing to the wealth of the state. These policies have undoubtedly been given impetus by the size of the state and the relatively small population it supports.

#### *Population*

The population of Western Australia at the 1971 census, was 1.03 million or 8.1 percent of the Australian population. Since the early 1960's in keeping with other western countries, the total fertility rate in Australia has shown a steady decline and recent reports indicate it is near zero population growth level. Population growth in Australia has been boosted by a continued policy of encouraging immigration, although immigration targets have been reduced in recent years. Western Australia has maintained a growth rate above the national average, primarily as a result of immigration from overseas and interstate but also because its change in fertility has lagged slightly behind the national trend. Thus, between the national census of 1966 and that of 1971, Western Australia maintained an annual growth rate of 3.91 percent against the national rate of 1.87 percent.

The population of Western Australia is highly centralized, 68.5 percent is concentrated in the Perth metropolis, and some 75 percent is on the coastal plain within 200 kilometers of the city. Being the commercial as well as the administrative center of Western Australia, and the only city within the 2.5 million square kilometer area, every major development in the state has caused growth within the State Capitol. Consequently, between the 1966 and 1971 census, Perth's population expanded at a rate faster than the state as a whole and in fact grew at a rate of 4.63 percent p.a.

#### **Western Australia—Water Resources Related to Land Use and Population.**

##### *Water resources regions and resource distribution*

Western Australia is one of the driest states in the Australian Commonwealth. The average annual discharge of the state's rivers is only  $50,000 \times 10^6 \text{m}^3$ , or 14½ percent of the national figure despite the fact that it occupies ⅓ of the land. Only a fraction of the surface water can be diverted to use.

Figure 2 illustrates an estimate of the usable potable surface and underground water resources, and their distribution. The distribution of resources is uneven and unfavorable.

As much as 72 percent of the usable resources are in the Kimberleys, a region of low population 2,000 km north of the main population center of the state. In that region the only major recognized mineral deposit is bauxite. Irrigation development in the Kimberleys is beset with problems of pest control, costs and marketing, and the ultimate potential is limited by a shortage of irrigable land.

The Canning Basin is a desert basin with little prospect for settlement whose underground water resources represent approximately 3 percent of the state's usable water.

The Pilbara/Murchison Region is a major development area of the state. Rapid growth has been stimulated by iron ore developments, by solar salt production and by promise of exploitation of off-shore natural gas. Although arid to semi-arid, and possessed of only about 3 percent of the usable water of the state, the Pilbara/Murchison is fortunate to have well defined river systems capable of being dammed and modest underground water resources.

A large area of the interior of the plateau or more than half of the state is all but devoid of water resources of more than local significance. Much of it comprises of a worn Archaean Shield which is riverless but for remnants of ancient drainages forming shallow salt pans. Gold mining development in this division at the turn of the last century was served with water by construction of a steel pipeline to pump water some 500 kilometers from the west coast near Perth. This system has since been expanded to serve the agricultural area of the hinterland and the recent growth of a nickel mining industry.

The South West Region, the most populated region of the state, enjoys 22 percent of the usable potable resources. In this region, the escarpment which separates the Perth Coastal Plain from the western edge of the plateau is dissected by short rivers and streams draining the southern forests (Figure 3). These rivers and the underground water of the coastal plain are the major components of the region's water resources.

##### *State-wide catchment management problems*

In the large pastoral areas of the Kimberley and Pilbara/Murchison Regions, the principal catchment management problem has been erosion and sediment transport resulting from over grazing.

The most noteworthy of these cases is the Ord River in the Kimberley Region (Figure 2) where the high sediment loads associated with such erosion created a threat to

the development of Lake Argyle, one of the two largest reservoirs in Australia.

In the more developed South West Region, water resources and land management problems take on a different degree of complexity in terms of technical, social, economic and environmental interactions. It is therefore proposed to discuss the South West Region in some detail.

## **PART 2 SOUTH WEST REGION, GENERAL DESCRIPTION OF WATER PROBLEMS**

### **South West Regional Water Resources— The Salinity Problem**

The magnitude, distribution, and salinity of the South West Region's water resources are depicted in Figure 4 in terms of the two major resource components namely: (i) The underground water in the deep sediments of the coastal plain; and (ii) the surface water resources of the rivers and streams whose catchments drain the south western margin of the Great Plateau.

The diagram depicts "usable resources," that is, supplies of water it is feasible to develop by some system of conventional design. Both components of water resources are of similar magnitude although surface water resources are the larger. The greatest concentration of resources is south of Perth and in the south-west corner of the region.

Figure 5 shows the distribution of the surface water component of the region's water resources. A notable aspect of this diagram is the magnitude of resources above the potable limit of total soluble salts. It will be seen that larger basins, which draw on areas further inland into the agricultural areas of the south west, tend to have higher salinities and may be saline, brackish or at least marginal in their salt content.

The development of high salinity in streamflows has resulted predominantly from the clearing of natural forest and woodlands east of the escarpment. Most clearing has been associated with land purchased from the Crown and cleared for production of cereal crops and improved pastures, a process which has continued steadily since colonization of the region in 1829.

In the mid 1960's the alienation of Crown Land on three major river basins of the region was halted. The limited scope of this action, by default, effectively defined a policy which "wrote off as lost" certain rivers of marginal salinity, and left others of major importance under threat. In retrospect, these actions were a rather belated and limited response to a problem which has long been recognized and which had been described with very clear perception by a railway engineer as far back as 1924 (Woods, 1924). In recent years, there has been intensive research activity on the salinity problem. However, this work has largely been spurred by the emergence of new

pressures on the catchments related to forest disease, utility development, bauxite mining, and wood chipping.

Figure 5 indicates that the salinity effects have been extensive and more than 50 percent of the usable surface water resources of the region may have suffered significant adverse effects through land use changes from forest to agriculture.

The increase in stream salinity results from an imbalance caused by increased drainage through the soil and rising water tables which are due to reduced transpiration after natural forest or woodland is removed. Salts are imported by rain and there tends to be a form of natural balance between saltfall and the salts carried away by streams, with some gradual accumulation of salts in the soil profile over thousands of years. The increase in groundwater movement after clearing releases stored salts into the streams by capillary rise and direct drainage. The time required for sufficient leaching of salts to re-establish a satisfactory balance with saltfall is expected to be in the order of several hundred years and too long to be of relevance to present day planning (Peck and Hurle, 1973).

### **South West Region Water Resources Related To Demand**

#### *Water use*

Urban water usage in this region is among the highest in terms of per capita consumption rate within Australia. Metropolitan Perth consumes on average 625 liters per capita per day of which a startling 55 percent is used on lawns and gardens, 20 percent on domestic usage and 25 percent on industry and commerce. Further south the irrigation schemes use 1600 liters of water to produce 1 liter of milk.

The average metropolitan household pays only 16 cents daily for the delivery of 2 tonnes of water compared with \$2.00 a day for fuel and energy and roughly \$4.00 a day for food. At present money values the price of water could increase threefold in the next 20 years but it seems likely that urban users will absorb such costs without marked changes in life style or water use. Irrigation water is currently sold for only 0.3 to 0.4 cents/m<sup>3</sup> and future irrigation use is much more likely to be affected by rising water values.

Total consumptive use in the region at the present time is approximately  $500 \times 10^6 \text{ m}^3/\text{year}$  of which 75 percent is drawn from state operated supplies. This use is dominated by the Perth metropolis which represents 44 percent of usage and irrigation which in total is a similar amount. A further 7 percent is pumped inland to towns and agricultural areas of the interior including the gold and nickel producing areas some 500 km from the coast. The remaining 5 percent of usage comes from other coastal towns.

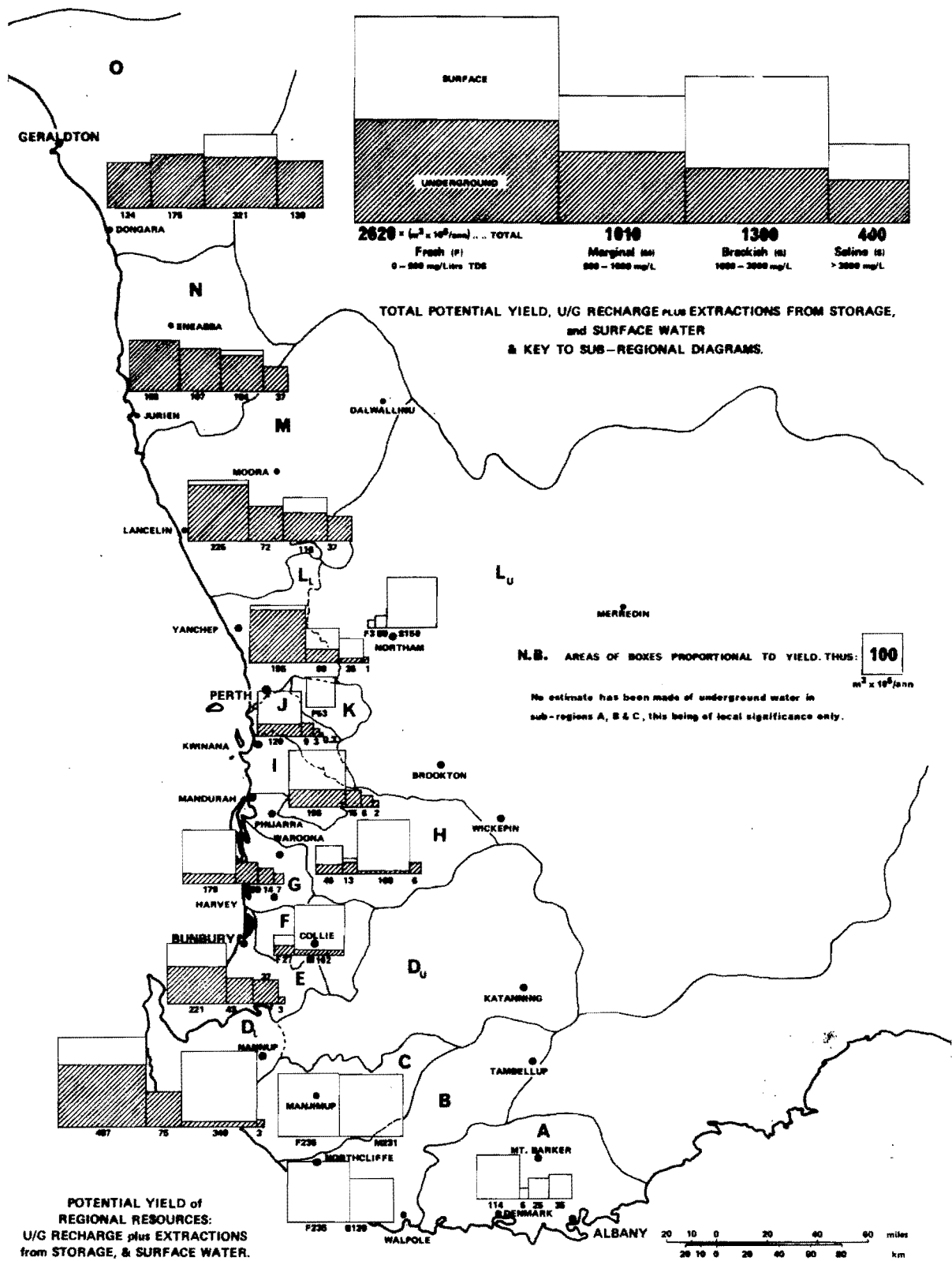


Figure 4.

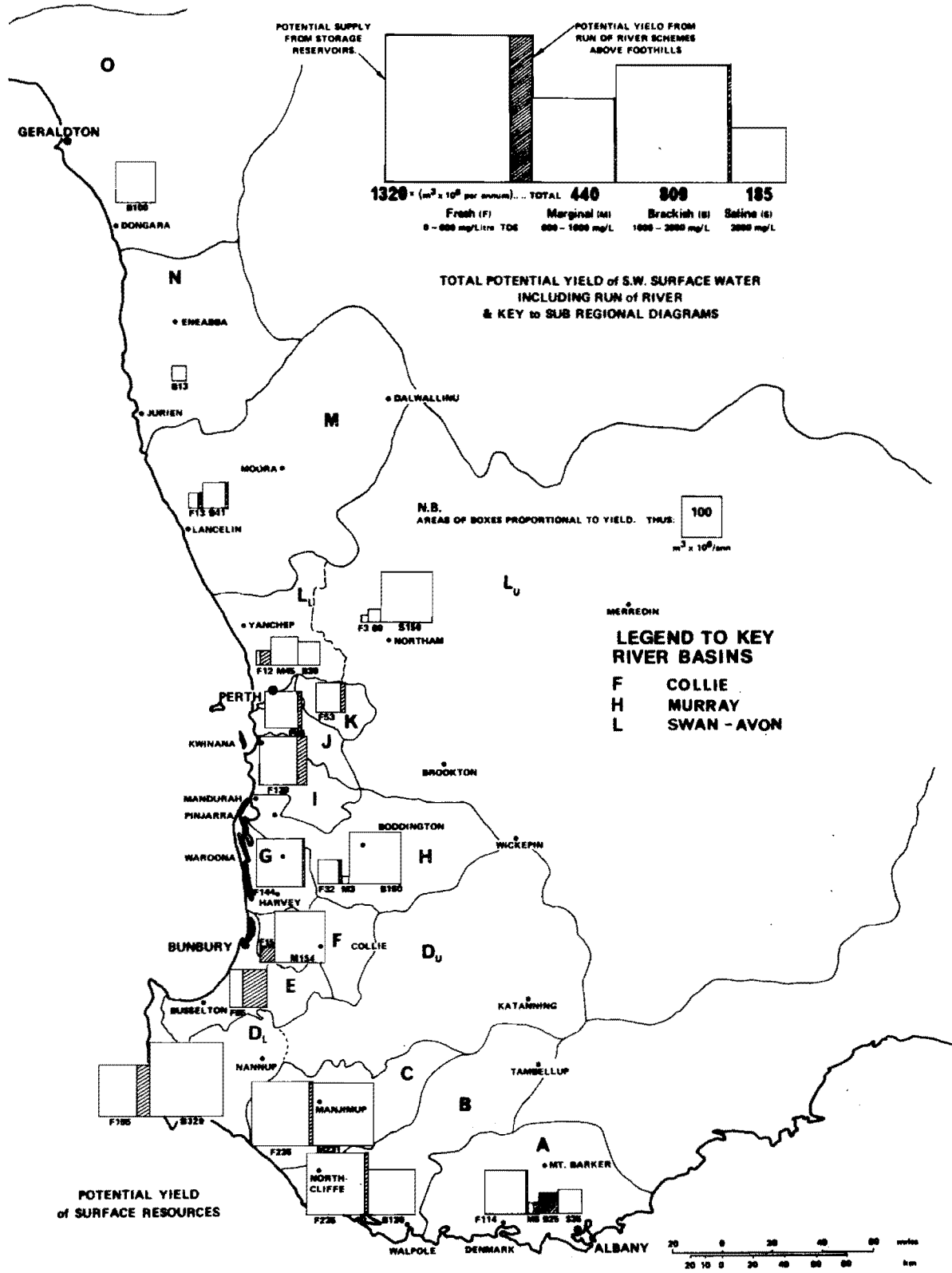


Figure 5.

A population of 850,000 is at present dependent on the water resources of this region.

The state has over-riding rights to the control and distribution of water resources and in the South West Region two closely allied state water authorities operate almost all public supplies. These are the Perth Metropolitan Water Board and the Public Works Department. The latter authority is responsible for irrigation and town supplies outside the Perth metropolitan area.

*Present consumption and future demand projections*

Figure 6 shows demands projected over a period of 30 years for the region and its individual basins up to 200 kilometers north of Perth. The demand projections which are plotted over resource scales, are intended to represent a continuation of present growth trends, objectives and water use patterns. The diagram is based on a population increase from about 850,000 to 2,300,000.

The diagram indicates that:

- (i) At present the usable water resources of the region are 20 percent exploited.
- (ii) Within about 30 years, the region's usable potable resources could be 50 percent exploited.
- (iii) The Perth subregion is approaching the point where demand exceeds supply, and the import of water from the southern region some 250 to 300 km south will become necessary. Well within this 30 year period, the water distribution problems will become complex, costs may rise sharply and water supplies will become regionally integrated.
- (iv) If fully exploited and redistributed to points of demand by a regional water system, the region's water resources would support about 5 million people on present water use patterns.

*Complications*

The foregoing review of the water resources situation is highly simplified and many other factors have a bearing on the future water situation. Some of the main adverse factors are:

- (i) The water resource inventory is not unchanging. Many factors, of which the salinity problems have been referred to as the most serious, have a bearing on the magnitude and quality of the usable resource. Mostly the effects are conflicting land uses and will tend to degrade the resource inventory.
- (ii) Environmental aspects, which include recreational conflicts, impacts on wetlands, drowning of specific types

of forested valleys and effects on rivers which may conceivably be nominated for retention in a natural state. At this stage, the extent of this complication can only be guessed, but is likely to be significant.

(iii) Directly conflicting site developments such as railways through dam sites and land settlement within potential reservoirs.

Some of the likely compensating factors are:

- (i) Slackening of population growth, and associated resource conflicts may slow the rate of development.
- (ii) Rising costs and changing social attitudes to wastage may cause some lowering in the high regional consumption rates when high utilization levels are reached.
- (iii) Alteration in acceptable water standards, particularly in relation to salinity and/or blending of brackish and fresh waters may extend the usable resources.
- (iv) Catchment management practices may achieve higher yields.
- (v) Civil engineering developments may enable exploitation of fresher flows in salt affected streams by such means as diverting saline head waters or separating saline water through use of stratification phenomena in reservoirs.

*Regional dynamics*

The foregoing simple description of water supply problems in the south west has emphasized that the problem is becoming regional in scope and that time as well as space is a basic dimension. The reference to complicating factors has indicated the relevance of positive (growth) and negative (control) feedback effects between water supply and other regional interests including considerations of a social, economic and environmental nature (Figure 7).

In systems terms, the description has been that of a dynamic regional socio-technical system (Forrester, 1968).

A way of decomposing this complex system into more manageable sub-problems is to divide it vertically into a hierarchy of regional, subregional and river basin planning and horizontally into functional sectors including water supply, land use, social and economic sectors. Further relevant division of the land use sector includes forestry, agriculture, mining, utilities, and environment.

In Western Australia, institutions are structured along the usual functional lines with single purpose governmental authorities representing each sector. Thus although there may be reasonably strong vertical links

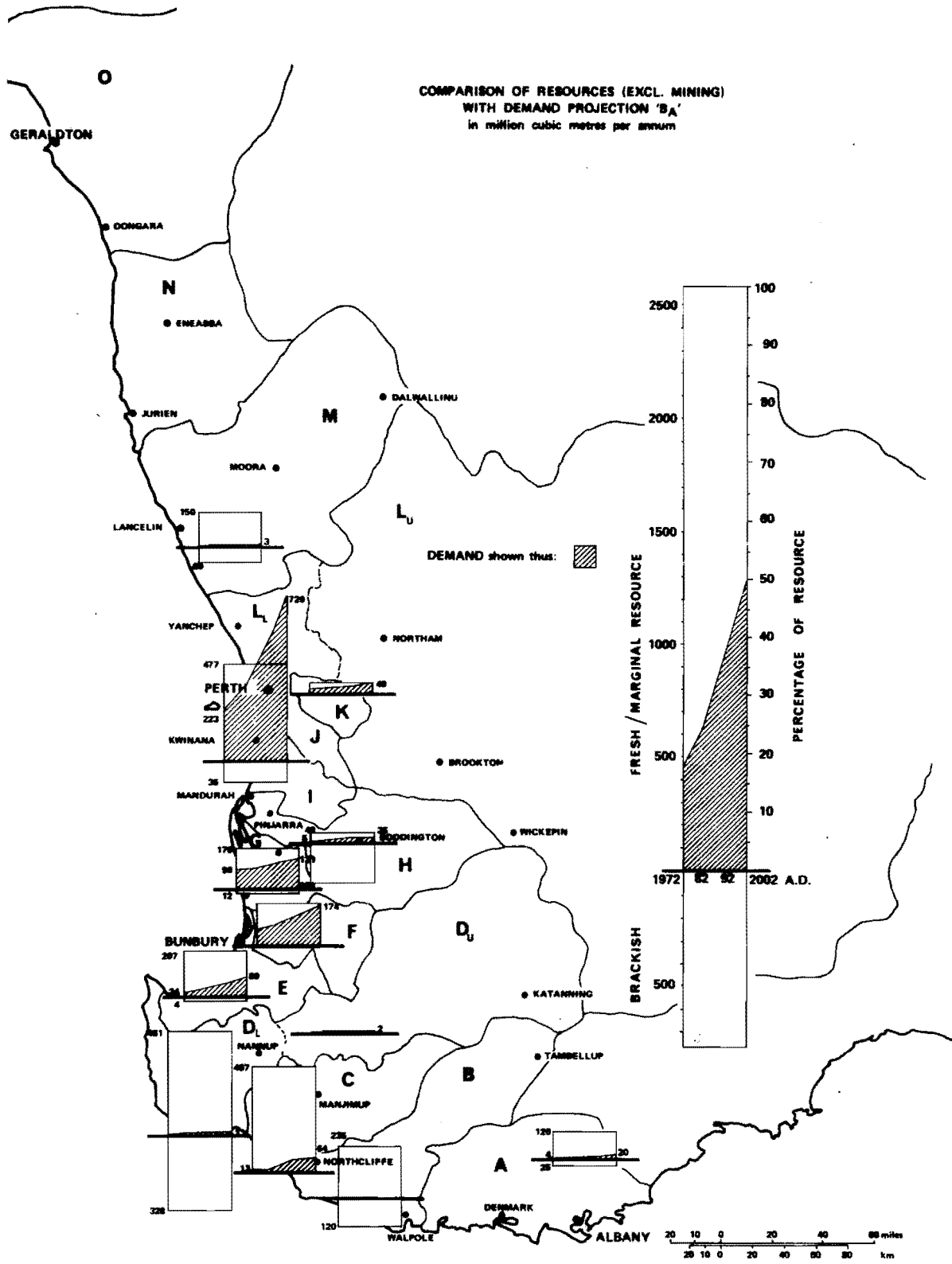
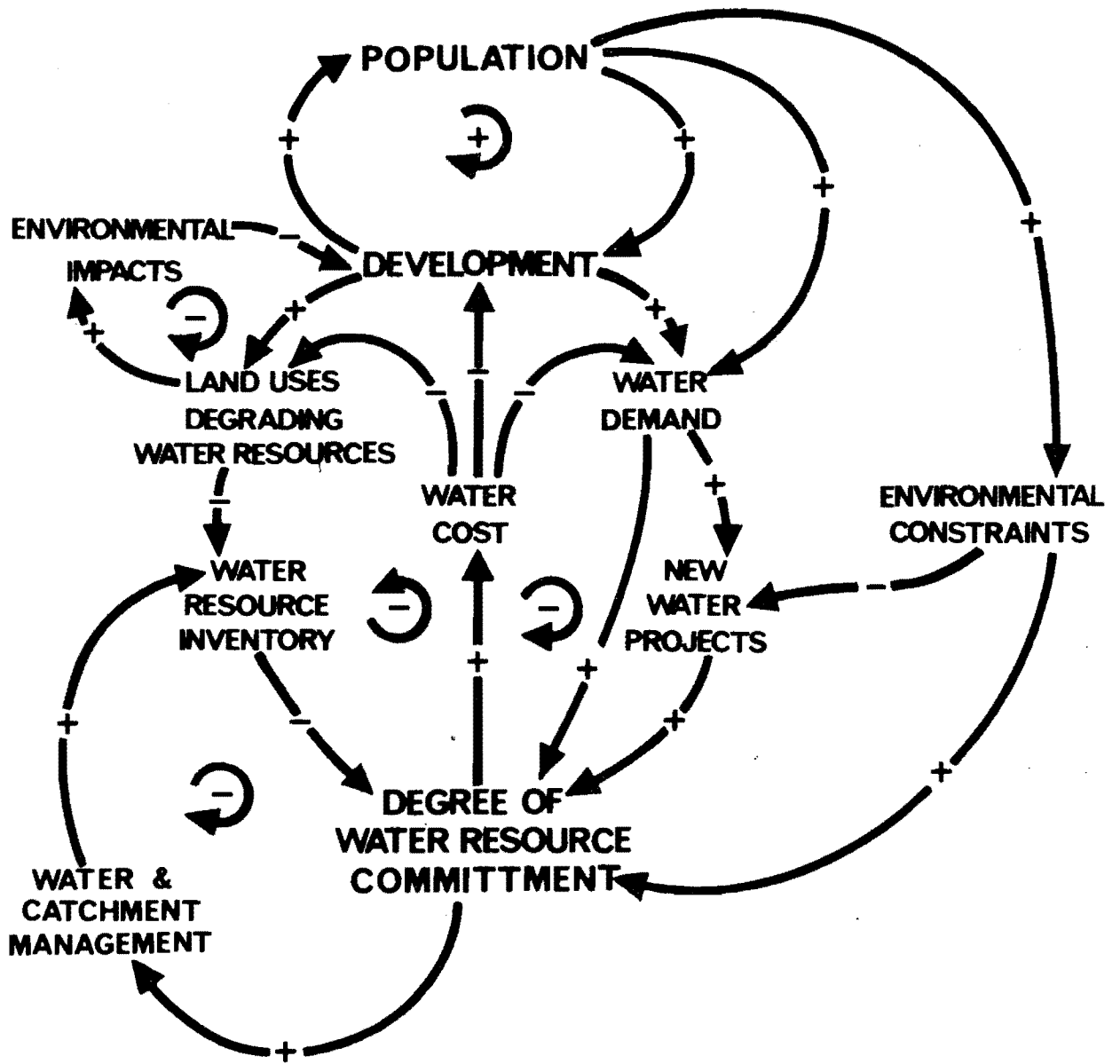


Figure 6.



**SIMPLIFIED DIGRAPH  
LAND USE - WATER RESOURCE  
SYSTEM**

Figure 7.

through various planning levels in some sectors, and personal communication and cooperation between the relatively small state authorities is good, the machinery for inter-sector coordinated planning is weak.

At the regional level, land use issues represent the greatest area of inter-sectoral conflict and have a major effect on the inventory of usable water resources. It is appropriate to focus further discussion on conflicts of the land use sector with water resources.

### **The Land Use Sector— A Review of Problems Related To Water**

#### *General*

Land use-water use conflicts in the South West affect both resources.

Land use has direct effects on the water resource inventory. The principal effects at the present time are on salinity, quantity of runoff, bacteriological quality, turbidity, and direct competition for the use of reservoir sites. Water use has less direct effects on the land resources, the principal ones being on environmental values and recreational activities. Indirect effects in the form of restrictions and controls directed at preserving water resources may have a significant impact on the use of land.

Where resource uses are in conflict, the policies of land use at any time will reflect society's, and the decision-makers', perceptions of the relative values of the resources within the regional system.

Characteristically in dynamic socio-technical systems, the decision-makers' perceptions of relative resource values lag behind changes in these values. Physical responses to policy changes also have a built in lag. Remedial management policies therefore tend to be introduced late and adverse effects tend to overshoot the desirable limit before being brought under control.

The aim of the planners should be to recognize and propose policies which respond to these changes sufficiently early to avoid serious overshoot.

Where conflicts occur between land use and water resources, controls will develop in a variety of ways and the responses on the supply side of the water sector may range from direct construction measures, through water and catchment management, to restrictive land policies. Responses on the demand side of the water sector are likely to be slow in developing but may range from public concern over wasteful water use, to adjustments in water standards, to declining water use resulting from rising costs and out migration.

The established and dominant resource problem in the South West Region is the problem of salinity associated

primarily with agricultural clearing. There has been considerable overshoot of this problem due to a slow response in formulation of management policies, delays in implementation, and time lag in the development of salinity problems.

There are now several newly emergent pressures on the use of the catchments. Recognizing the erosion of water resource values which has already occurred, these pressures need to be managed with sufficient foresight to allow for lags and delays inherent in the socio-technical system.

Land use conflicts with water resources are further discussed under the headings of agriculture; forestry; mining; utilities; recreation and environmental sectors.

#### *Agricultural sector*

Agricultural development in the form of annual pastures and cereal crops is extensive, particularly in the eastern parts of the catchment areas. Even ignoring the Swan-Avon Basin (Figure 5, Basin L) which drains the most inland areas, in excess of 50 percent of the total catchment area is under extensive farming development. The impact is greatest on the major rivers of the region which drain the hinterland. The smaller scarpland catchments are the least affected.

By far the principal problem associated with agriculture is salinity. Another potential problem which is now being studied is the possible effect of nutrients in runoff from agricultural lands on eutrophication of the Peel Inlet, a large estuary which is a major recreation area for the Perth metropolis.

There has been a tendency in this region for subjective decisions to be made in relation to land policies and their effect on salinity along the lines that: (i) increases in salinity of fresh streams are acceptable if small, because there is no apparent loss involved; (ii) increases in salinity of marginal and brackish streams are often tolerated because the resource is already above water supply standards and superficially there is no loss involved; and (iii) increases in salinity which move fresh streams into the marginal category are given greater attention because they represent a more obvious loss of resource.

These simplistic policies are inadequate because they fail to recognize that in any of the three cases a loss of quality represents a loss of capability for blending waters to acceptable limits and therefore effectively represents a loss of total resource. In any case they reflect a blind application of standards rather than a realization that rising salinity represents either true increases in costs or lost opportunities in forms of use.

A fresh water resource can be regarded as having a potential magnitude which is its magnitude after blending



with an otherwise unacceptable water. Simple calculations can show that, without a corresponding increase in runoff, a gain of only 50 mg/l in the salinity of a fresh stream can represent in the order of a 5 percent loss in its potential resource magnitude. Thus, any increase in salinity whether the water is fresh, marginal or brackish represents a loss to the total usable water resource inventory.

The problems of salinity and the potential effects of clearing on salinity of streamflows tend to increase as one moves inland towards the areas most suitable for agriculture.

The effects of agriculture have therefore been extremely damaging. In the wide valleys of the agricultural areas, salt storage in the soil is usually high and saline water tables more accessible to the river drainages.

The Murray catchment (Figure 5, Basin H) is one of the most significant examples of the problems of agricultural development in relation to water catchments. The river if dammed could alone develop a yield of approximately  $200 \times 10^6 \text{m}^3/\text{year}$ . This quantity is greater than the current total consumption of the Perth Metropolitan Water Supply or more than 10 percent of the usable potable water in the entire region. However, the salinity level on this stream is now such that a reservoir could only supply water with an average total salts content of 1500 mg/l and clearing in the catchment is still continuing.

Prior to agricultural development this major river would have yielded potable supplies, and its decline in quality has represented a major tradeoff to regional development. It does not follow that the land development was unjustified, but the example serves to emphasize the dynamic nature of resource values in a developing region. In earlier years the land was unquestionably more valuable for agriculture, than as a water source. However, increased demand for water and the loss of water resources through agricultural development have raised the value of remaining water resources relative to the value of the land for agriculture.

A second and highly significant catchment, where agricultural clearing is actually threatening an established water scheme is the Collie River (Figure 5, Basin F).

This again is a major river on which the second largest storage reservoir of the region is built and develops a yield of  $100 \times 10^6 \text{m}^3/\text{year}$ . The potential yield of the river is  $150 \times 10^6 \text{m}^3/\text{year}$  or 8.5 percent of the total usable potable surface water resources of the region.

The waters of this catchment are currently used for supply to the inland and for irrigation on the coastal plain, but some of its resources may ultimately be used in a

coastal plain water supply system dominated by the Perth metropolis.

Release of land for agriculture on this catchment has been halted because of rising salinity. However, land already alienated is still being cleared and the problem continues to develop (Figure 8). Current assessments indicate that existing clearing on this stream may result in a rise in average total salts content to between 550 and 950 mg/l. If all existing alienated land is cleared, the salinity may rise to between 800 and 1700 mg/l.

The range of possible solutions or partial solutions for the problems of this water source include changes in pasture, repurchase of farm lands for regeneration of forest or woodlands, engineering diversions of saline waters, exploitation of reservoir stratification to separate saline water, blending with more potable sources or development of an alternative source.

The ultimate balance in the use of this catchment and means by which it is achieved will be dependent on the perceived regional value of its water compared with other land products. As an immediate holding measure, consideration is being given to imposing a moratorium on further clearing of alienated land until the alternatives have been more thoroughly investigated. Such a moratorium is within the powers of existing statutes but raises economic and social problems of the possible adverse effects on economic viability of the farmers.

The action of imposing a moratorium on this specific catchment may be viewed as a reaction indicative of a lack of adequate land use planning. The question immediately arises as to whether such a moratorium should not be more extensive and also directed to other catchments where problems could otherwise develop in the future.

#### *Forestry sector*

In the South West Region, forestry operations are regarded as highly compatible with water resource management, despite the high transpiration levels and consequently low runoff from forest catchments. The existence of managed hardwood forests behind the scarplands has ensured the maintenance of fresh non-turbid streams of high bacteriological quality. Because of the low runoffs, the possibility of yield improvement by thinning or removal of forest, or by other management practices is of interest. However, because of potential salinity problems this potential strategy is probably confined to shorter scarplands streams.

Although increasing controls may begin to limit the growth of the agricultural clearing in the eastern half of the catchments which has had serious effects on salinity, there is a newly emergent group of problems all incident on the previously secure State Forest Lands. These problems are associated with forest disease, wood chipping, bauxite

# CLEARING ON COLLIE RIVER CATCHMENT

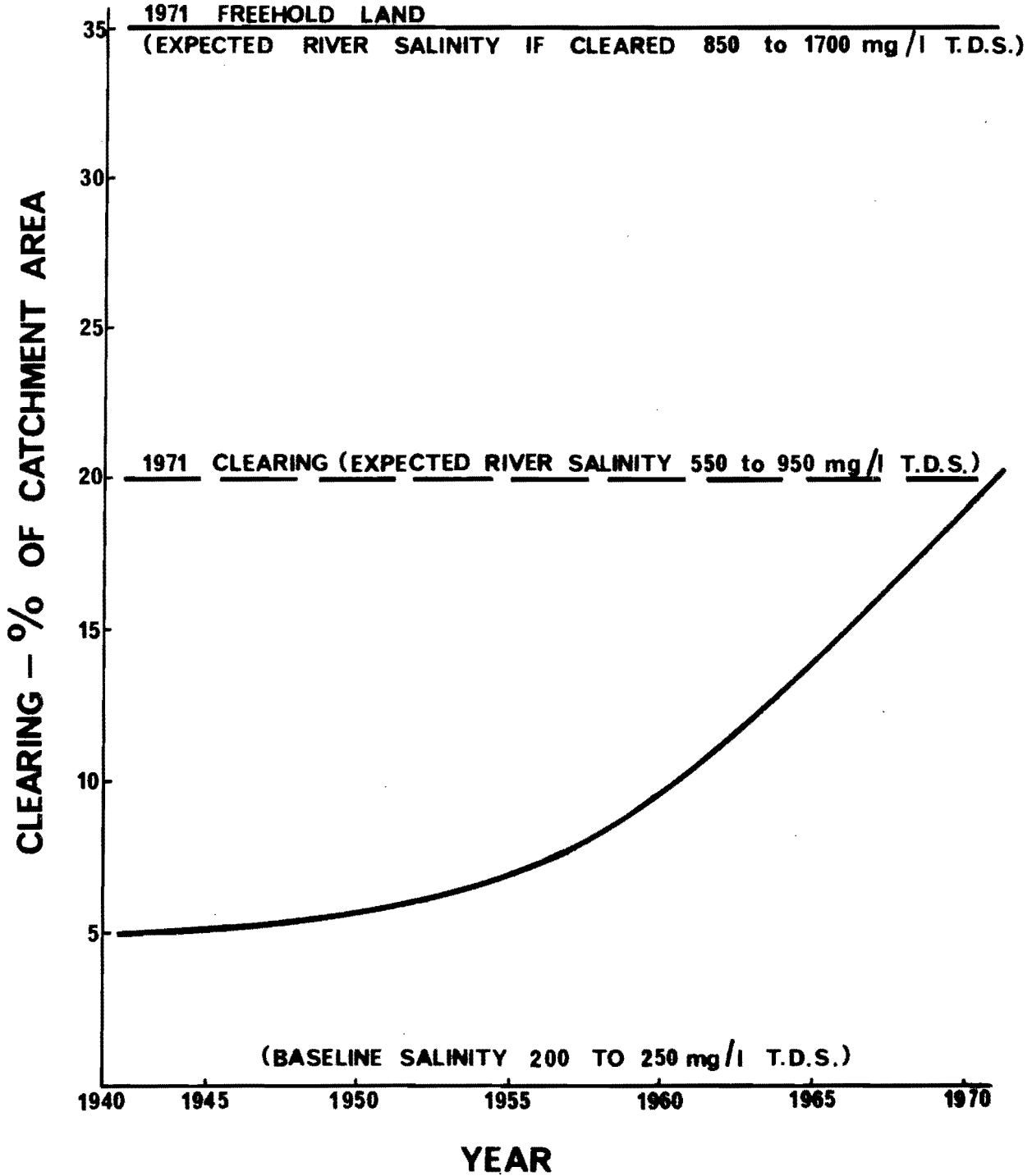


Figure 8.

mining, and utility developments. Regarded separately, some of these operations are not of great significance, but collectively they leave very little of the forest lands free of new pressures.

The greatest long term problem in the forest management sector of the water catchments is the widespread "dieback" or "root rot" disease caused by *Phytophthora cinnamomi*. This disease is fatal to jarrah, the hardwood eucalypt which is the dominant of a major sector of the south-west forests and to a number of understory species. More than 1700 sq. kilometers or about 10 percent of the forest is affected. The disease is most severe towards the western areas of the forest, but is widely dispersed, particularly along drainage lines. Its effects may ultimately cover much larger areas of the catchments.

Unmanaged, the effects of die-back on salinity could be severe, as the loss of vigorous forest could produce similar effects to agricultural clearing. Fortunately at the present time the "dieback" disease is most active in the western parts of the forest where salinity effects may be less serious.

Present forest management practice involves strict forest hygiene measures and replacement of diseased forest with tolerant species both native and exotic. In a further bid to control the spread of dieback, temporary quarantines have been placed on large areas of healthy forests. These quarantines may ultimately become more selective.

A second pressure on the forest areas, which is at present the subject of a degree of environmental controversy, is a wood chip operation in the southern forests. This operation covers a license area of 4900 square km or 27 percent of the forest area and involves a mixed logging and wood chip operations which during a 15 year initial license period will cut over and regenerate about 110 square km of forest annually.

Opponents of the wood chip scheme have argued its possible effects on salinity. Experience and present understanding of the hydrologic processes suggests that wood chipping will not produce any significant lasting effects on salinity. Regeneration is expected to quickly restore the transpirative balance and some of the areas recognizable as most sensitive for salinity are being avoided initially whilst research continues.

A point of argument has been raised in relation to wood chip which is relevant to all conflicting resource problems in this area.

It was argued that the project involved a risk of major losses to water and other environmental resources. The resources at risk were highly rated relative to the assessed economic returns of wood chips. The situation was thus likened to an inverted lottery where the prize is certain but

small and the cost of the ticket is not known with certainty but could be ruinously high. Few people would buy tickets in such a lottery.

We now know sufficient of the wood chip impacts to recognize that the damage to water resources which could conceivably be associated with the industry is overrated in this argument. However, the underlying principle is an important one and it would be a valid and useful test for all developments in this region to attempt comparison of the expectation of loss (value of loss time probability) with the expectation of benefits.

#### *Bauxite mining*

Bauxite mining leases were granted during the 1960's over nearly 50 percent of the State Forest. Agreements established with the mining companies were ratified by State Parliament and override other statutes. The agreements set a lower limit but no upper limit on mining rate and provide 21 year leases with rights of renewal for 2 further periods. The Lateritic Plateau, much of which is potentially suited for bauxite mining is the most extensive land unit in the forest area. The soils consist of a thin sandy gravel over a lateritic cap and a friable mottled zone which is the main ore body. These in turn are underlain by a pallid kaolinitic zone. All materials are developed from decomposed basement rock. Bauxite is removed by open cast mining to a depth varying from 2 to 9 meters. The sandy topsoils are removed before mining and immediately replaced on the surface of the restored pits.

Based on planning figures for mining development, an area of roughly 120 square km or 0.7 percent of forest areas will be directly affected by bauxite mining and associated roads over the next 25 years. Secondary and more extensive effects of bauxite development, such as hydrologic effects on surrounding vegetation and spreading of dieback by mining and particularly by exploration activity, are existent.

At present the Lateritic Plateau is a land unit where dieback has made limited progress and where the healthiest areas of productive jarrah forest are found.

Some time will lapse before the direct effects of bauxite mining on water resources are extensive. However, marked changes in the local hydrologic regime may be expected. The Lateritic Plateau acts as "sponge" which absorbs and stores much of the winter rains until transpired during the summer months. This is a very dominant feature of the regional hydrology and results in low runoffs and very low flood intensities.

Removal of the bauxite mantle removes this capacity to absorb the winter rains. Present regenerative procedures based on contour banking, deep ripping and replanting are aimed at minimizing runoff by re-establishing the capacity of the soil to absorb rainfall. The

objective of these measures is to minimize problems of erosion and of turbidity in the surface runoff.

However, it remains to be established whether the regenerative practices are in all cases sound with respect to salinity development. Encouraging water movement into the ground may promote problems with saline seepage. The clay layer which, after removal of bauxite, becomes the immediate subsoil, is the horizon where salts tend to have been deposited. The danger of salinity development under these regenerative practices would probably increase markedly in an inland direction.

The problem of regeneration in abandoned bauxite mining pits is complex and is being extensively researched. It would appear possible, as indicated above, that there are conflicting objectives in regenerative practices and some tradeoffs in current water resource values may occur in balancing out these conflicts.

There would seem to be good arguments for concentrating bauxite mining in the western areas of forests where dieback is most severe, where salinity problems are least likely and runoff improvement a more promising prospect.

It is conceivable that in the long term the effects of bauxite mining and other potentially runoff inducing land uses may require upgrading of spillways on some water supply dams.

#### *Utility development*

A further 110 square km or 0.6 percent of forest has been lost to utility development over the past 20 years. Most significant are power transmission routes and roads which due to their linear nature, present a serious threat by increasing the rate of infection of healthy forest by dieback disease. Practices such as repurchase of appropriate agricultural land for re-forestation can offset the direct loss of forest. However the secondary effects on forest disease may be far more significant than the direct effect of forest removal.

#### *Recreation and environment*

Water supply development in the region has not emphasized recreational use of water other than providing passive enjoyment in barbecue and picnic facilities near the dam walls. Recreational activity which may lead to pollution of the water supply is not permitted and the public is directed away from the reservoir perimeters. It is only on irrigation reservoirs that boating, fishing and swimming have been permitted.

Reservoir sites are necessarily constructed in the valley sections where rivers approach the escarpment and cut progressively deeper into the plateau. These natural reaches of river valley are highly attractive and are used

for canoeing, swimming, fishing, picnicing, and wild camping. In consequence the development of storage reservoirs which are closed to active recreation are also recognized as impediments to continuation of established recreational activity and there is an awakening opposition to their establishment in those sectors of the community most affected.

The closed policy has persisted in the region because of the proximity of extensive coastal beaches and the fact that some natural water courses have so far remained available for recreation.

Recreational conflicts may be expected to further develop as population rises and the proportion of streams developed for water supply increases. Public recreation may be particularly strong in respect of future reservoirs developed for export of water from one subregion to another.

In this region not many rivers can be left wild, but it is apparent that the stage is being reached where the community might accept the cost of reserving some streams and will accept the cost of water treatment as a reasonable price for recreational use of water supply reservoirs. Water supply authorities will need to broaden their base of operations to consider recreational use of water as much a part of their customer demand as is urban water supply or irrigation.

Environmental implications of water development other than direct aesthetic and recreational implications have not received much attention up to the present time. This is partly a reflection of past attitudes to environmental matters in the Australian society and partly because no major conflicts have been recognized.

However, it is apparent that conservation issues will begin to impose some constraints as development continues. Because reservoir sites are selected by their physical and topographic features they tend to be developed always in one specific valley type. In consequence they come into conflict with the conservation of vegetation systems peculiar to that valley situation and ultimately with the preservation of certain endemic species.

There are current proposals before the State Environmental Protection Authority for development of a large national park and wilderness areas in the lower reaches of six major rivers of the south coast. The resources of these rivers represent some 40 percent of the usable potable surface resources of the South West Region. Although dam sites on these rivers are upstream of the proposed reservation, it must be expected that development of the rivers will have some impact on the proposed park and on estuaries and wetlands within its area. Superficial assessments suggest that water development and conservation are not in major conflict, and with

some compromises both resource uses can be suitably planned.

It is evident that environmental considerations are an important land use factor related to future water resource utilization in the region. Water allocations to conservation purposes, whatever form they take, may be regarded by water authorities as another form of water use the cost of which will have to be passed on to the consuming public.

### PART 3—TOWARDS A SOLUTION

#### The Need For Study

The foregoing discussion has emphasized the water resource-land use problems of the South West Region as a collection of complex problems within a dynamic regional socio-technical system.

The problem is seen to contain most of the basic conflicts so commonly recognizable in present day resource management. It includes: problems of comparing values of renewable and nonrenewable resources; problems of valuing social benefits and disbenefits; problems of comparing the value of environmental and economic assets; and uncertainty in prediction of physical consequences of man's activities.

The problem involves both research effort and planning effort. It is somewhat paradoxical that although Australia is a technologically advanced nation and there is a considerable amount of high caliber research studying the physical problems of this region, the machinery for comprehensive inter-sector planning and decision-making is nonexistent. There has been only a very slow advance from the frontier approach, towards viewing the region's catchment lands as a complex and highly developed system.

There is now a growing recognition among the sector authorities that the planning problems of this region have reached a stage where a formalized approach to multi-sector planning of land use is necessary and can be justified. Underlying this recognition is a growing level of public discussion of the problems, and a public expectation that such planning should take place.

Both research and planning require an ongoing commitment.

#### Research

Research effort is being concentrated on the problems of land use and water salinity. Catchment monitoring and basic research into the general process of salinity development and control is being supplemented by specific research into the effects of bauxite mining, wood chipping and restorative practices.

The Commonwealth Scientific and Industrial Research Organization in collaboration with State Authorities is also undertaking research into the application of systems analysis methodology to land resources management in the region. (Bennett, Batini, Sharpe, and Havel, 1973).

#### Planning For Land Use and Water Use

##### General

The regional framework of this problem has been emphasized in the presentation of this paper as has the need for multi-objective planning.

The regional framework is seen as relevant not just in the downward sense that forward projection of regional development affects the demand for development in the land and water use sectors. It is also important in the upward sense that future regional population and life style will be significantly affected by planning policies in these sectors.

Assessments of future values of resources such as water need to be determined at the regional level. We assume that water as a resource is highly valued. However, this is not at present reflected in current cost and usage.

##### Methodology

Discussions have begun between the sector authorities as to how the coordinated planning problems should be approached. Emphasis is being given to the planning of land use employing some appropriate systems methodologies.

The thrust of this paper has been to emphasize the regional and multi-objective aspects of the problem and the need for a tiered approach to planning.

Within such a hierarchical system of regional planning, reconnaissance planning of land use, water supply and related sectors needs to be initiated at a regional and sub-regional level. Where particular basins such as the Collie Basin (F) or Murray Basin (H) are seen to warrant specific attention, more detailed planning can proceed within, and feed back to, the regional planning activity.

In this complex problem, optimization is a Utopian goal. Planning processes will follow a step wise movement towards reasonably well balanced solutions. Such a situation may favor methods which assess and illustrate to decision-makers the regional futures associated with alternative policies. However, wherever systems analysis is utilized, the primary benefits of its use may flow from convening a multi-sector team to study and work at describing the problem and alternative solutions in a sufficiently rigorous manner to enable computer analysis.

*Institutional problems*

There are problems in establishing a suitable coordinating framework for such inter-sectoral planning. These problems relate not only to the creation of a workable administrative system but also to acceptance by administrators of the necessary commitment of sufficient staff resources at an appropriate level.

**CONCLUSIONS**

The South West Region of Western Australia is an example of a major Australian region where water resource and catchment management problems are highly complex and where pressures on limited resources are rapidly increasing due to long developing as well as newly emergent conflicts.

The region has been described as a dynamic socio-technical system. Within that system, it has been suggested that as development progresses, the water supply sector will need to look increasingly for solution of its problems to considerations outside its own sector.

The size of the water resources inventory is dynamic and the era has already been reached where catchment management is as relevant as water resource development in forward planning. Furthermore, the time may arise when social and economic adjustments provide one of the major alternative responses to water supply problems.

Past attitudes to land use have been influenced by the size and the low population density of Australia, and Western Australia. At the present time, although high caliber research is taking place, coordinated regional land use planning is lacking. The land use and water sector authorities are searching for a planning framework within which to work. There is growing public interest in the problems and the region is now at the cross-roads where such a framework may be established. Before such a step can proceed, institutional problems will need to be faced and a course of action decided.

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## **Session II**

### **Hydrology: State of the Science**

# Assessment of Areal Rainfall

*Colin L. Pierrehumbert\**

## INTRODUCTION

Attempts to quantitatively measure precipitation have been made in various parts of the world for at least several hundreds, and possibly thousands of years, but even so it remains one of the most difficult elements to measure accurately. Even if we exclude snow, which contributes significantly to the annual precipitation over less than 10 percent of Australia, there are still considerable difficulties in obtaining accurate measurements of point rainfall. Because of the extreme variability of rainfall both in time and in space even greater difficulties are encountered when estimates of rainfall over catchment areas are required. This paper concentrates on the estimation of rainfall, as distinct from snow, hail, and other forms of precipitation, over areas from less than one square kilometer to several hundred square kilometers.

## MEASUREMENT OF POINT RAINFALL

The standard method of measuring point rainfall, which has remained basically unaltered for more than 100 years, is to catch rainfall in a funnel of known cross section and to measure the volume of the catch. However the shape, size, material, and method of exposing the funnel vary from country to country and the method of measuring the volume of the catch varies from instrument to instrument, depending on the purpose for which the observation is made. Other methods of measuring point rainfall such as the distrometer, which provides data regarding drop size as well as rainfall intensity, are also used but these are, in general, research rather than network instruments. Radar is introducing new possibilities for areal rainfall measurement but assessment procedures are still experimental.

One of the main problems in measuring rainfall is that as soon as a device to collect rainfall is exposed it disturbs the airflow in the immediate vicinity and so influences the catch. This problem can be partly overcome by the use of "pit gages" but these instruments require more space and maintenance than do the normal gages. For these reasons they are not used as network instruments. The alteration

to the catch is not a constant one as it is dependent on a number of factors including wind speed and direction, gage height, exposure relative to neighboring buildings, slope and aspect of the gage site and the rainfall intensity. These problems are described in some detail by Rodda (1971) and it suffices here to say that the alteration to the catch is almost always a decrease and in extreme conditions may be greater than 30 percent. This means that the rainfall as measured by a standard gage should never be considered to be an accurate measure of the rainfall but only as an "index" of the rainfall amount. This fact is usually not important when comparing rainfalls at different, well exposed, observing points, particularly when total rainfalls for periods of a week or more are being considered. It can, however, be quite important when considering rainfall as input to a rainfall-runoff model and even when comparing observations at different gages for periods of a few hours.

## SPATIAL VARIABILITY OF RAINFALL

The variability of rainfall in space has received only a limited amount of attention in Australia. Maher (1968) calculated correlation coefficients for annual rainfalls for some 50 stations throughout Australia compared with a number of key stations and drew isopleths of correlation coefficient. He demonstrated that correlation coefficients of 0.5 or more could extend several hundreds of kilometers from the key station and, in the case of Alice Springs, the 0.25 correlation coefficient enclosed half the continent.

Body (1966) investigated the decrease in correlation coefficient between rainfalls at neighboring stations in north coastal New South Wales. He found that for yearly and monthly rainfalls the correlation coefficients were of the order of 0.8 or higher for stations up to 80 kilometers apart. However, when rainfalls for storms of 2 or 3 days were considered the correlation coefficients decreased more rapidly with distance. He found coefficients to be typically 0.75 at 30 kilometers, falling to about 0.3 at 80 kilometers.

When shorter time periods are investigated the problem is complicated by the fact that the temporal patterns of storm rainfall can differ markedly between stations as little as 50 kilometers apart. There is also the complication that it is not uncommon for rain to fall for a

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period of hours at one station while a neighboring station receives little or no rain.

An examination was made of clock hour data for some 20 stations in the Melbourne metropolitan area. In this study clock hour falls of the order of 10 millimeters or more were correlated with the heaviest one hour fall on the same day at other stations. This analysis indicated little correlation between stations even when they were 5 kilometers or less apart. It must be emphasized that this study was confined to rainfalls selected almost entirely from shower type situations and that these results cannot be applied to clock hour rainfalls in general. However it is considered most unlikely for significant correlation to exist between clock hour observations for stations more than 10 kilometers apart.

#### **REPRESENTATIVENESS OF POINT RAINFALL OBSERVATIONS**

Apart from problems related to erosion produced by the physical impact of the raindrops, we are usually interested not in point rainfall but in rainfall over an area. As it is impossible to directly measure rainfall over an area greater than a few square meters, it is necessary to estimate areal rainfall either from a limited number of point observations or by the use of radar techniques.

The cost of maintaining a network of rainfall stations increases with the number of stations in the network. It is not surprising, therefore, that considerable effort has been directed towards the establishment of criteria for the spacing of recording sites to give the maximum information from the minimum number of gages. The World Meteorological Organization (1965) has laid down guidelines, based mainly on experience gained by various Meteorological Services, for station densities for network purposes under a wide range of conditions. Hendrick and Comer (1970) following earlier workers have suggested that spacing should be based on the decay rate of the correlation coefficients between rainfalls at neighboring stations. They suggest that the distance between gages should be such that the correlation coefficients between gages for rainfalls for the duration of interest are 0.9 or better.

If a criterion of this nature is used it can be shown that over the area studied by Body (1966) stations located 45 kilometers apart will provide satisfactory estimates of monthly or annual rainfall. However to obtain a similar accuracy for rainfall totals for 2 or 3 days storms the stations need to be not more than 15 kilometers apart, or, in other words, a nine-fold increase in station density is required. When the duration of interest is reduced to a day or less a still higher station density with stations not more than 5 kilometers apart is required to maintain the same order of accuracy.

The area studied by Body was in reasonably hilly but not particularly rugged country. It is reasonable to assume

that over flatter inland areas the rates of decay of the correlation coefficients with distance are less and therefore similar accuracies would be obtained with a less dense network. In more mountainous terrain the rainfalls tend to vary more rapidly with distance and usually exhibit some correlation with elevation. It is therefore usually necessary to increase the station density in mountainous terrain to maintain similar accuracy.

#### **USE OF RAINFALL DATA IN CATCHMENT HYDROLOGY**

There are three distinct uses of rainfall data in catchment hydrology. These are:

(1) In estimating the input of water into the soil for pastoral and agricultural purposes. For this purpose monthly rainfall data will often suffice although on some occasions more detailed data will be required.

(2) For input to rainfall-runoff models. These can be used to estimate stream flow which, in turn, can be used in land use and erosion studies. For this purpose data for calendar days is the minimum requirement with data for shorter durations being preferable.

(3) For use in erosion studies where the energy of the rain drops is the prime consideration. For this purpose data for durations of not more than a calendar day is required with data for shorter periods being preferable.

For estimating the input of moisture to the soil, particularly when durations of a week or more are being considered it is usually sufficient to consider only point rainfalls for a small number of stations to obtain a satisfactory estimate. For example a single raingage will give a satisfactory estimate for catchments up to about 10 square kilometers while five suitably located stations will provide adequate information for a 200 square kilometer catchment in most instances.

For input to rainfall-runoff models, particularly when the model requires data for periods of a few hours, the estimation of areal rainfalls is more complicated. This problem is discussed in more detail in a later section.

For use in erosion studies it is usual to assume that the frequencies of point rainfall intensity events can be applied to a general area although the time of actual occurrences cannot.

#### **ESTIMATION OF AREAL RAINFALL**

Several methods of estimating areal rainfalls from point measurements have been proposed over the years and since the advent of high speed computers a number of more sophisticated methods have been suggested. Hall (1972) reviewed 15 such methods and a selection of these are set out in Table 1.

Table 1.

Method	Comment
Isohyetal Average	The most accurate available method. However very time consuming. Can be computerized with some loss of accuracy.
Arithmetic Average	Simple and easy to use. Requires fairly dense and relatively even geographical distribution of stations to produce reliable results.
Thiessen Polygon Average	Allows for variation in station density but cannot make allowance for ungaged areas of maximum rainfall which frequently occur. Time consuming as weighting factors must be recomputed for every combination of reporting stations. However it is readily computerized without loss of accuracy.
Abbreviated Isopercentual Average	The Thiessen weight for each station is modified by the ratio of the mean catchment average rainfall to the mean rainfall over the Thiessen polygons. This method allows a standard adjustment for orographic and other effects which do not change greatly from storm to storm.
Orographic Thiessen Polygon Average	The Thiessen polygons are determined by elevation rather than by distances between stations.
Multiple Regression Analysis Average	Weighting factors are based on multiple regression coefficients. These are obtained from a multiple regression equation using the "least squares method." Areal rainfall the isohyetal method is the dependent variable and station rainfalls are the independent variables. Simple to use, particularly in a computerized model.
Percent to Mean Annual Catchment Average	Isopercentuals of mean annual rainfall are constructed and the storm rainfall is calculated as a percentage of annual average.
Variation of the Abbreviated Isopercentual Average	This method is similar to the Thiessen method except that the weighting factors are calculated from the contribution to the mean annual rainfall over the catchment from each Thiessen polygon.
Inclined Plane Average	This method uses the centroid height of planes formed by erecting verticals corresponding to the rainfall at each gage at the apex of the triangle. This method is identical to the triangulation method described by Brunt (1964).
Centre of Gravity Average	This method uses the inverse of distance of a station from the centroid of the catchment as the appropriate weighting factor. It falls down when there is a station at or near the centroid as this station has a weight approaching infinity.
Correlation Thiessen Polygon Average	This method uses polygons constructed to points where the correlation coefficients between the stations are equal.
Correlation-Influence Function Analysis Average	This is similar to the Correlation Thiessen Polygon method but uses the assumption that interstation correlation declines with distance from the station.
Trend Surface Analysis Average	This method involves the fitting of a polynomial surface to the rainfalls at the observation points. This surface is used to estimate the average catchment rainfall.

Brunt (1964) compared four of the more commonly used techniques, namely, Arithmetic Average, Thiessen Polygons, Triangulation, and Subjectives Isohyets on two areas in south eastern Queensland. The areas chosen were involved in a cloud seeding experiment and therefore a fairly dense and evenly distributed network of gaging stations was available. The gage density was about one per 60 square kilometers and analysis periods were of the order of 3 weeks. Under these conditions Brunt concluded:

- (a) All four methods produced estimates within 5 percent of one another.
- (b) Arithmetic average was by far the fastest method.
- (c) The time taken for Thiessen Polygons and for the Triangulation method (after appropriate weights have been calculated) is about 2½ times that of the arithmetic average method.
- (d) The isohyetal method was almost 100 times slower than the arithmetic average method.

The conditions of the experiment outlined above are superior to those normally experienced. Where the gage density is not reasonably uniform the arithmetic average will not produce reliable results. Also, all stations reported for all periods considered, a situation rarely encountered with the average network.

Brunt performed all of his calculations using only a desk calculator. The time differential between the methods, although remaining in the same ratio, are unimportant in a computer environment where the slowest method of computation requires only a few seconds.

Most of the methods outlined in Table 1 give satisfactory results when used under appropriate conditions although some, such as the Centre of Gravity Average method, were found to be unsatisfactory under most conditions.

The choice of method will usually depend on: (a) the time available for the estimation procedure; (b) the

availability of computing facilities; (c) the size of the catchment; (d) the distribution of gages within the network; and (e) the accuracy required.

The Australian Bureau of Meteorology uses the Isohyetal Average method when time is available and high accuracy is required. When a large number of storms is being investigated a computerized version of the Isohyetal Average method is used (Body, 1973). In this method a "first guess" field is calculated by using a multiple regression equation in which the independent variables are the location (x-and y- coordinates) and the elevation while the dependent variable is the station rainfall. This field is modified using an influence function approach to provide estimates of rainfall for each of a series of grid points. The mean catchment rainfall is then the arithmetic average of the rainfalls estimated at each grid point within the catchment. This method is useful when there is an adequate coverage of stations (20 or more in and around the catchment) and 10 or more storms are to be investigated.

When estimates of catchment rainfall are required in a "real time" situation, for example for flood forecasting purposes urgency demands operational streamlining and a simpler approach is required. In such situations it is usual for a network of four or five stations to be used to estimate catchment rainfall using either a regression weight or a Thiessen polygon approach. This gives an accuracy of perhaps 20 percent but this loss of accuracy is offset by an 80 percent reduction in cost of reports and ease of calculation.

It has been shown by Body (1966) that five rainfall stations are sufficient to give a reasonable estimate of mean catchment rainfall for storms of two or more days duration for catchments in size from 100 to several thousand square kilometers. For shorter duration the accuracy provided by this method is obviously less. However, for very small catchments observations for two or even one gage can often suffice to give required accuracy.

#### **ERRORS IN AREAL RAINFALL**

Regardless of the method used to estimate areal rainfall there are a number of errors which can effect the estimate. These are: (a) Systematic errors due to the exposure of individual rainfall stations; (b) systematic errors due to geographic locations of the gages; and (c) random errors which are dependent upon storm type and rainfall distribution within the storm.

The systematic errors are caused mainly by poor siting. Strong winds will invariably cause gages to under record the rainfall but the magnitude of the underestimate will depend to some extent on the exposure of the instrument.

In most situations rain gage sites are selected either because observers are available to maintain the gage or the

site is readily accessible either by road or other means of transport. Thus the stations tend to be in the lower areas of a catchment or follow the settlement pattern (Learmonth, 1960). In such cases gages tend to be representative only of part of the catchment and frequently it is that part where the rainfall is lowest. A deliberate effort must therefore be made to site gages in more representative locations, particularly now that more reliable long term recording instruments are becoming available.

Random errors due to the spatial distribution of rainfall within the storm are most prevalent in shower type situations. It is possible for example for a storm producing more than 20 millimeters of rainfall to occur between two stations 10 kilometers apart and to produce little or no rain at the gage sites.

#### **RADAR ASSESSMENT OF RAINFALL**

Raindrops produce a discernible radar reflection and the intensity of the reflected signal is proportional to the sixth power of the diameter of the drops. As the rainfall is approximately proportional to the cube of the drop diameters it is possible to use the radar signal strength to ascertain the rainfall rate provided we have an adequate knowledge of the raindrop size distribution.

Currently, measurement of rainfall by radar is being done in Australia only on an experimental basis (Hall and Barclay, 1975). The Melbourne radar is used to estimate rainfall intensities every few minutes over "bins" which subtend an angle of 2.5 degrees of arc at the radar site and can be either 300, 600, or 1200 meters in length. The areas of the bins vary with the distance from the radar site but at 50 kilometers, the bin sizes range from approximately 0.6 to 2.5 square kilometers. Radar rainfalls are compared with observations from a network of 20 pluviographs located in a test area approximately 20 kilometers by 40 kilometers located to the southwest of the radar site. An accuracy of better than 30 percent is being obtained on most occasions.

The absolute range of the radar is about 400 kilometers but beyond about 200 kilometers the accuracy of the estimates of rainfall intensity begin to decline. This means that estimates of rainfall over catchment areas of 10 square kilometers or more with an accuracy of about 30 percent can be made, at least on an experimental basis, over a total area approaching 30,000 square kilometers from a single radar site.

It is anticipated that further development work both in defining the raindrop spectra and in the radar equipment itself will enable greater accuracy and resolution to be obtained. Within the next decade it should be possible to obtain estimates of twice the resolution and accuracy obtainable today over selected basins on demand.

### CONCLUSIONS

Annual and monthly rainfalls are well correlated over distances up to several hundreds of kilometers with correlation coefficients being of the order of 0.6 for stations 100 kilometers apart. Where rainfalls for a month or longer period are required a station density of 1 per 1000 square kilometers will provide satisfactory estimates for most purposes.

Rainfalls for 2 or 3 day storms are reasonably well correlated over distances up to 40 kilometers but beyond this distance correlation coefficients are rarely higher than 0.5. A station density of 1 per 100 square kilometers or better is often necessary to obtain reliable estimates of areal rainfall for such storms.

Daily and hourly rainfalls show some correlation up to 20 kilometers or even further in situations associated with general rain but are poorly correlated even at 10 kilometers in shower type situations. To obtain reasonable estimates of rainfall for these durations a station density of 1 per 25 square kilometers or better will often be necessary.

Over rugged terrain the fact that rainfall normally varies markedly with elevation will necessitate careful selection of gaging sites to ensure adequate sampling. It will also usually be necessary to increase the gage density to obtain the required accuracy.

The most accurate method currently available to estimate areal rainfall is the Isohyetal Average method. However this method is very time consuming and is not practical in an operational environment. Methods using weights calculated from Thiessen polygons or using regression techniques can be used successfully operationally. For many purposes satisfactory estimates can be obtained using data for four or five stations only, even when considering an area of several hundreds of square kilometers. This is particularly true when accuracy is

traded against the cost of obtaining observations in a "real time" environment.

Although the use of radar for estimating areal rainfall is still in the experimental stage in Australia the technique shows considerable promise. It is expected that within the next 10 years it will be possible to obtain estimates on demand of areal rainfall over selected basins to an accuracy of better than 20 percent using radar techniques.

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# Precipitation on Intermountain Rangeland in the Western United States

*Kenneth G. Renard and Donald L. Brakensiek\**

Precipitation in its many forms is crucial to the water supply which maintains life of the Earth. As a result, scientists have devoted much attention over the years to collecting information about precipitation. The continents of the Earth receives about 72 cm/yr of precipitation (Sellers, 1965) and the United States receives 76 cm/yr, very near the continental average. Unfortunately, most of the rangeland areas of the United States receive considerably less and have unique problems of seasonal and orographic distributions which limit forage production.

In this paper, we did not attempt the impossible task of providing an exhaustive catalog of all recent progress in precipitation analysis. Rather, we selected those sectors about which we, the writers, were most knowledgeable with the danger that this sample is doubtlessly biased. We believe that the sample is sufficiently large to reflect the current state-of-the-art, and further, point out some of the difficulties in analyzing precipitation with the tremendous temporal and spatial variability encountered in the basin and range topography of the Western United States.

Often, precipitation total, as measured with a recording gage, is not the parameter which is informative to the range user; rather, it is the amount of infiltration which is potentially available for plant growth. However, such parameters are not widely available. Most of the precipitation analysis and models developed by hydrologists are intended as input to hydrologic models, i.e., models intended to generate streamflow. Many of these findings can, however, be used for range management.

Because the physical processes involved in precipitation generation are not completely known and are exceedingly complex, the analyst often resorts to using statistical tools. Franz (1971) said that "...rainfall characteristics are often very difficult to mimic with statistical tools currently available. Empirical adjustments and a proliferation of parameters must often be used to obtain an acceptable level of performance. Considerable judgment and trial-and-error testing will be required for

some time to come in the development and in the application of these models."

The characteristics of precipitation in the rangeland areas of the United States are varied and depend on the atmospheric moisture source, season of the year, and elevation, among other things (Figure 1). Thus, much winter moisture in the U.S. western rangeland areas (generally west of the 100th meridian) results from Pacific Ocean moisture carried into the area by prevailing westerly winds (Battan, 1974). These winds may result in orographic precipitation patterns with more rainfall and greater snowfall at high elevations. Figure 1 illustrates the marked change in seasonal pattern (reflecting the different moisture sources from north (Spokane) to south (Tucson)).

At other times of the year (especially in the Southwestern U.S.), the atmospheric moisture results from a slow air movement from the Bermuda high pressure area toward a thermal low pressure area, often called the "Las Vegas thermal low" by meteorologists. Thunderstorms are prevalent during such atmospheric conditions and produce the summer peak like that shown for Tucson on the distribution graph (Figure 1). Thunderstorms come in many sizes, shapes, and structures and fall into two broad categories: local (air-mass) and organized (frontal) thunderstorms. Local storms are fairly isolated storms with a short lifetime, high intensity rain, and limited areal distribution. One or a group of organized thunderstorms implies a longer lifetime than the local storm. Organized storms form in lines or bands of thunderstorms, sometimes called "squall lines." They often initiate along, or ahead of, a cold front and nearly parallel to it.

Such differences in precipitation types and moisture sources require different analyses. Thus, the subsequent discussions are divided between Southwest thunderstorms and non-thunderstorms (interior northwest precipitation) with a review for each.

## THUNDERSTORM PRECIPITATION

The local type (air-mass thunderstorms often lead disappointed ranchers and farmers to state that it has

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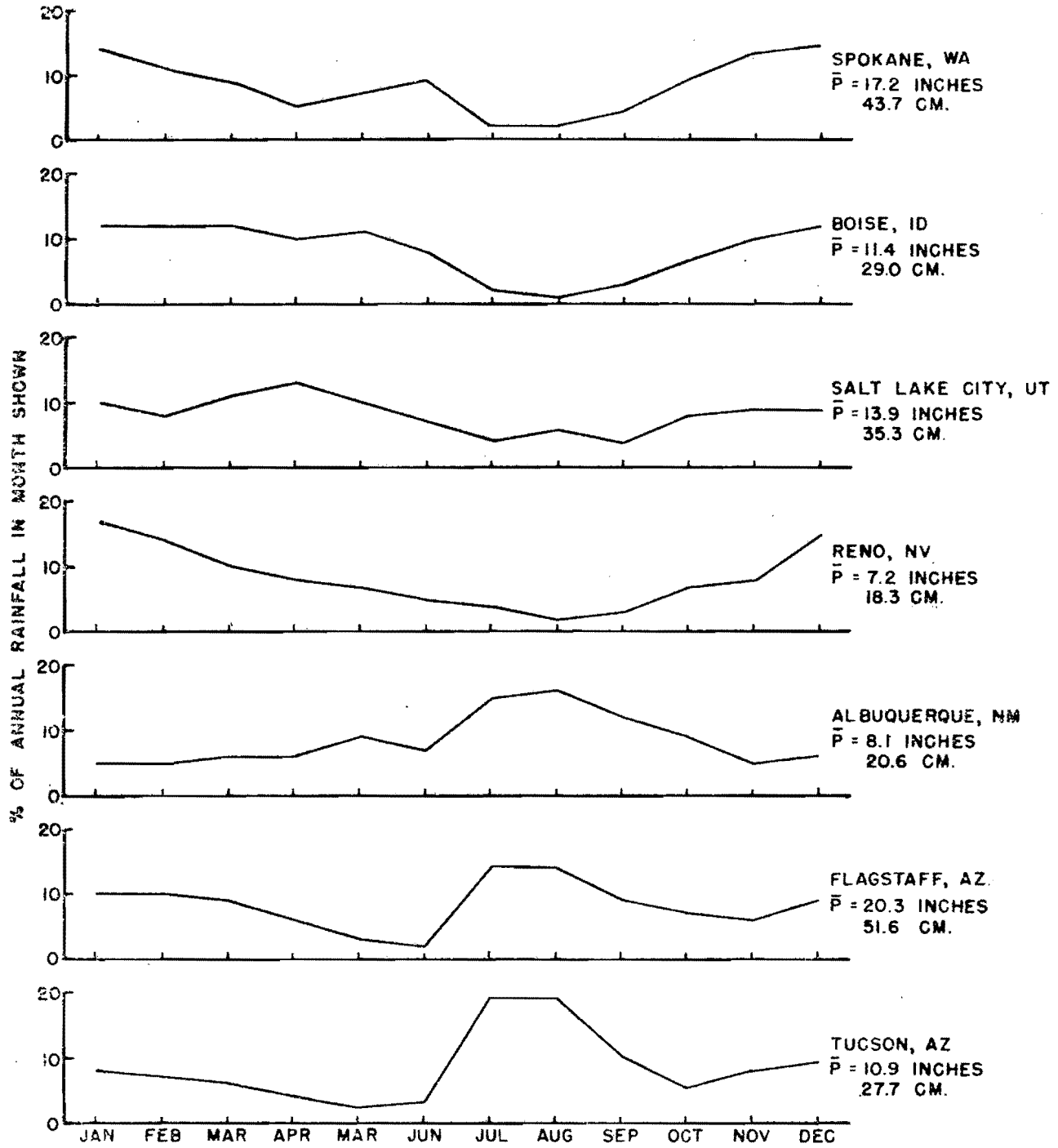


Figure 1. Distribution of annual precipitation at select stations in intermountain areas of the Western U.S.

rained everywhere but on their ranch. Exclamations like "we were completely surrounded by storms but somehow they all veered around us and we didn't get a drop all afternoon" are quite common. McDonald (1959) described this thunderstorm illusion with a graphical model similar to the following discussion. Fifty thunderstorms were randomly located in a 25,900 km<sup>2</sup> (10,000 mi<sup>2</sup>) area (161 x 161 km or 100 x 100 mi) using a table of random numbers. In level country, true air-mass thunderstorms are apparently randomly located. Because McDonald was concerned simply with the impression left in the observer's mind, it was not necessary to specify whether the storms or each observer's observation occurred simultaneously. Rather, the storms may have occurred at randomly distributed times over some duration, like an afternoon. Osborn, Lane, and Kagan (1971) observed that on the Walnut Gulch Experimental Watershed in southeastern Arizona, the air-mass thunderstorm beginning times are normally distributed with mean and standard deviations of 1700 and 3.5 hours, respectively.

On the storm map (Figure 2), five observers were randomly located with a table of random numbers with the constraint that each observer be at least 40.25 km (25 mi) from any boundary point of the square (each observer was presumably able to detect storms 40.25 km from his location), so the observer's circle of shower detection lies within the model area.

Inspection of Figure 2 shows that each observer except #1, will observe storms fairly well distributed around the horizon. To illustrate this, the storm positions were measured with a protractor and plotted in the lower portion of Figure 2. The number of observed showers ranged from 4 (observer #1) to 12 (observer #2) (Figure 2). In addition to seeing fewer storms, observer #1 was surrounded by two quadrants without any storms, with observer #3 having one quadrant (SW) without any storms. McDonald showed with probability theory that only 8 percent of all observer-quadrants will be storm-free in the model.

The expected value for the number of storms detected per circle is 9.82, whereas the mean for the five observers was 9.4. However, only 5.9 percent of the entire model area received rain, i.e., the probability was only 0.059 that rain will actually fall upon any observer.

Hershfield (1962) showed that the coefficient of variation (standard deviation divided by the mean) of annual precipitation is generally larger in the western U.S., as illustrated in Figure 3. The paucity of gages in this mountainous area may tend to smooth the actual variability somewhat but it does illustrate the role of thunderstorms in contributing to such variability. A series of monthly, water-year, or growing-season rainfalls would be most useful to range scientists planning range utilization programs. Hershfield stated, "the ideal procedure then would be to use a theoretical distribution. . .to

construct a series of maps, with isohyetal patterns at least as complex as those of the mean map, for several probability levels. However, this would be a rather expensive project, which no one had considered important enough to undertake."

This later objective was partially fulfilled in a Regional Research Report prepared by members of the staffs at each land-grant institution in the west (Gifford, Ashcroft, and Magnuson, 1967). They obtained the probability of various precipitation amounts for weekly periods in various time intervals of a year at select stations in the Western U.S. Rather than constructing iso-probability lines, they estimated precipitation for each station and distance for which the data can be reliably extrapolated. They used a smoothing technique with a weighted 3-week moving average in which double weight was given to the week under consideration. This technique eliminated some of the random variations in the probabilities that result from using a short 30-year record for each station. This same Regional Research Committee also produced a report (Heerman, Finkner, Hiler, 1971) giving the probabilities of sequences of wet and dry days which may be helpful to range scientists.

#### THUNDERSTORM PRECIPITATION MODELING

Thunderstorm precipitation can best be described by realizing that three elements are necessary: describing the distribution of (1) rainfall events, (2) depths, and (3) the areal distribution pattern. Because of the complex physical laws involved in rainfall processes, hydrologists generally use a probabilistic description of a local variable to predict the statistical properties of future rainfall. Small rainfall amounts are important to most rangeland plant species and, therefore, many precipitation models designed to predict large basin runoff present an incomplete picture of the precipitation distribution (e.g., Lane and Osborn, 1972, Duckstein et al., 1972).

Figure 4 illustrates the spatial variability of a thunderstorm on the Walnut Gulch Experimental Watershed in Southeastern Arizona, and shows the annual precipitation totals at certain gages, which include numerous thunderstorms and some winter frontal storms. Each small circle represents a recording rain gage on the 150 km<sup>2</sup> (58 mi<sup>2</sup>) area and its immediate vicinity with each gage approximately 1.4 km (0.9 mi) apart.

The storm of July 16, 1967, had 6.83 cm (2.69 in) at the center in 69 min, with 2.82 cm (1.11 in) occurring in 20 min. The maximum intensity of 18.3 cm/hr (7.2 in/hr) for several minutes is typical of these thunderstorms. Variability like this leads to highly variable annual totals in relatively short distances with annual maximum and minimum often only a few miles apart and the maximum often twice the minimum. In 1967, the maximum was only 60 percent more than the minimum. No definitive pattern

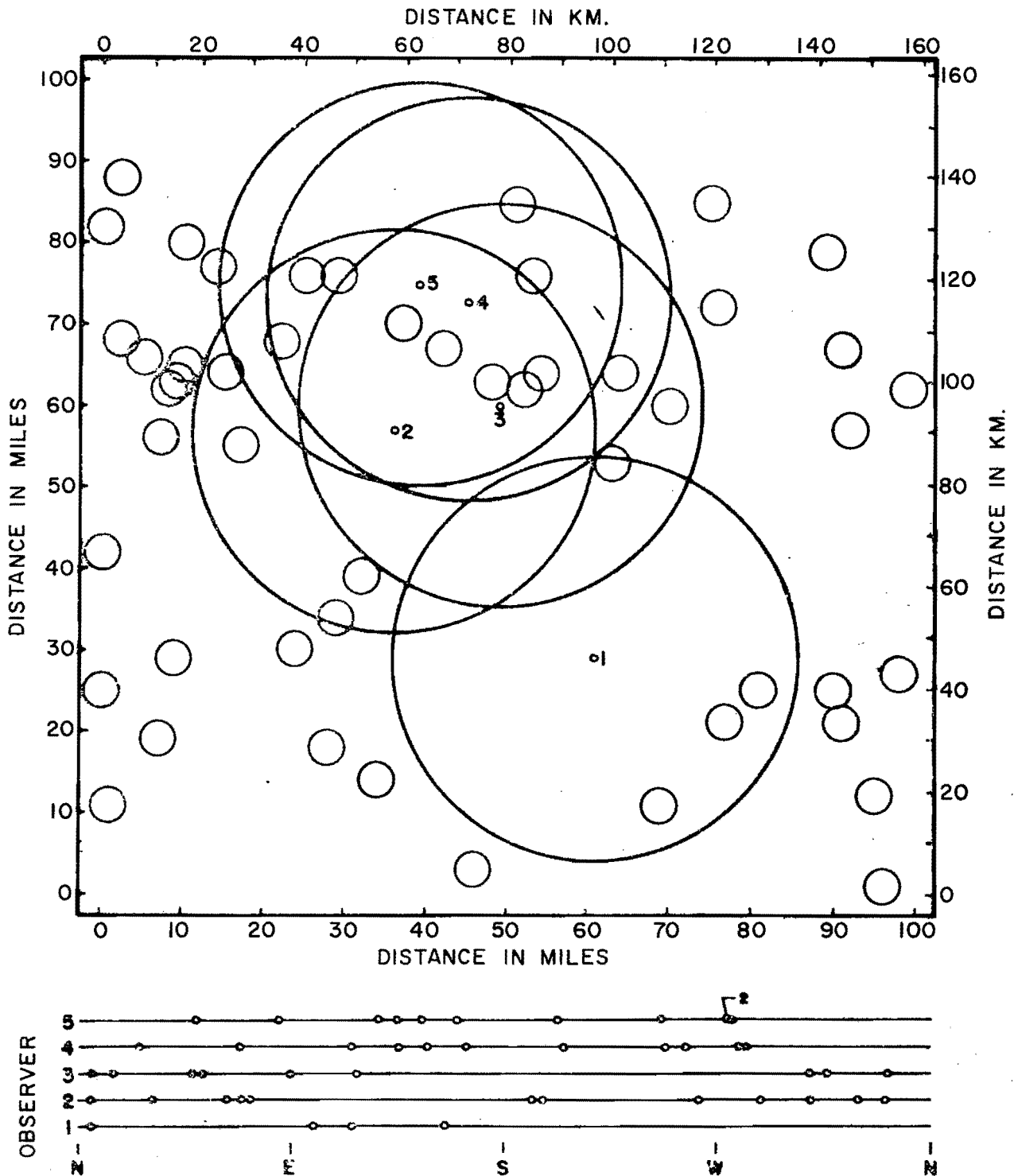


Figure 2. Hypothetical storm map showing the location of 50 thunderstorms with five observers randomly located. Each observer circle was 25 miles radius while each storm had a 1-mile radius. The lower portion shows the location of the storms in relation to each observer. (After McDonald, 1959).



for the occurrences has been discernible statistically on Walnut Gulch.

#### Distribution of Rainfall Events

Weiss (1964) and others found sequences of wet and dry periods are best described by a Markov chain probability model. Smith and Schreiber (1973) like Hershfield (1970) showed that a Markov chain adequately described air-mass thunderstorm rainfall in addition to the frontal-type situations. They also showed that in addition to describing the beginning of the summer "rainy" season in southeastern Arizona, the Markov model also gave a good fit to the cumulative distribution of wet days per season for the Tombstone rain gage (Figure 5), with 73 yr of data. Figure 5 also shows that the Markov model better fitted the historical data than did the independent (Bernoulli) daily model. The Bernoulli model also consistently overpredicted the probability of the starting day of the "monsoon" season. The Markov model with segmented nonhomogeneity was obtained by partitioning the wet and dry probabilities during the season which improved the fit of the historical data as compared with using the average wet and dry probability throughout the season.

#### Distribution of Rainfall Depths

Rainfall depths for periods of 1 day and longer are generally widely available in publications, like the climatological reports of the National Weather Service. Accordingly, many hydrologists and meteorologists have investigated expressions for the maximum precipitation

depths and have developed simulation models to predict the depth as input to runoff models. Table 1 shows examples of such approaches. Some of the differences in the distributions found to describe the maximum precipitation depths (Table 1) are undoubtedly associated with differences in the precipitation source involved (i.e., frontal versus air-mass thunderstorms) and with differences in precipitation type (i.e., snow versus rain).

Mixed distributions have been suggested by Hawkins (1971), Singh (1968 and 1971), and others to describe hydrologic processes which are notoriously non-normal. The problem has an old and honorable history dating back to the eminent statistician Pearson (1894) but because of the laborious calculations necessary for accurate solution, it has received only limited application.

That hydrologic variables are not normally distributed should not be surprising. Hawkins (1971) quoted Reich (1969) on this problem:

Nature has no back room boy dictating that flood series (or precipitation depths) should follow a particular law. . . Rather let us visualize. . . mathematical functions for what they are—merely a continuation of man's efforts at curve fitting.

In an extension of their 1973 work on thunderstorm occurrence, Smith and Schreiber (1974) showed that the seasonal rainfall depth for three gages located in southeastern Arizona was describable with a compound or mixed exponential distribution of the form shown in Figure 6. All of the curves shown (Figure 6) may be approximated by two segments divided by some point of inflection,  $X_c$ , or a mixed exponential of the form

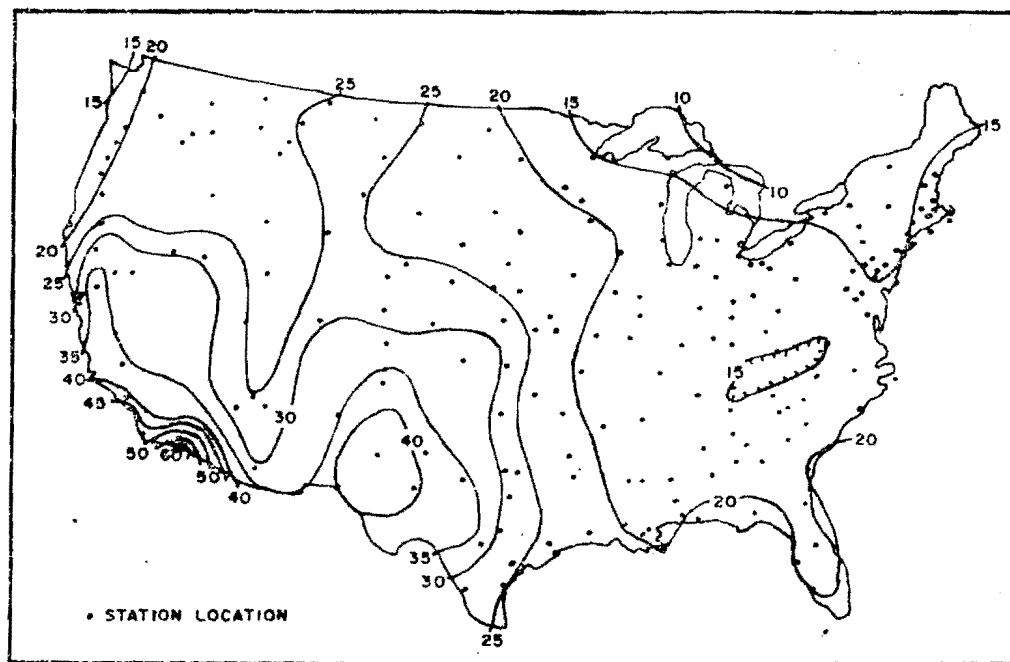


Figure 3. Coefficient of variations of annual precipitation in percent. (Hershfield, 1962).

$$P(X \geq x) = 1 - ae^{-\lambda_1 x} - (1-a)e^{-\lambda_2 x} \dots (1)$$

(Woolhiser, 1975). The very skewed shape of the density function increases the uncertainty of the sample probabilities as depth of rainfall increased.

Smith and Schreiber (1974) stated that this model, "... could be used in practical watershed management for this hydrologic region to estimate the probability of extreme drought or wet seasonal rainfall, which is relatively indeterminate from short records." Further

work is presently underway at the Southwest Watershed Research Center to extend this model beyond the area of its limited initial testing.

Hydrologic variables (especially precipitation) are almost always the result of countless causes or factors, like the phenomena causing thunderstorms vs. phenomena causing general low-intensity, frontal rain and snow. Such variables, therefore, can be measured as sampling either the combined effects of several phenomena in a single sample or sampling different phenomena separately over time in a combined sample like with precipitation.

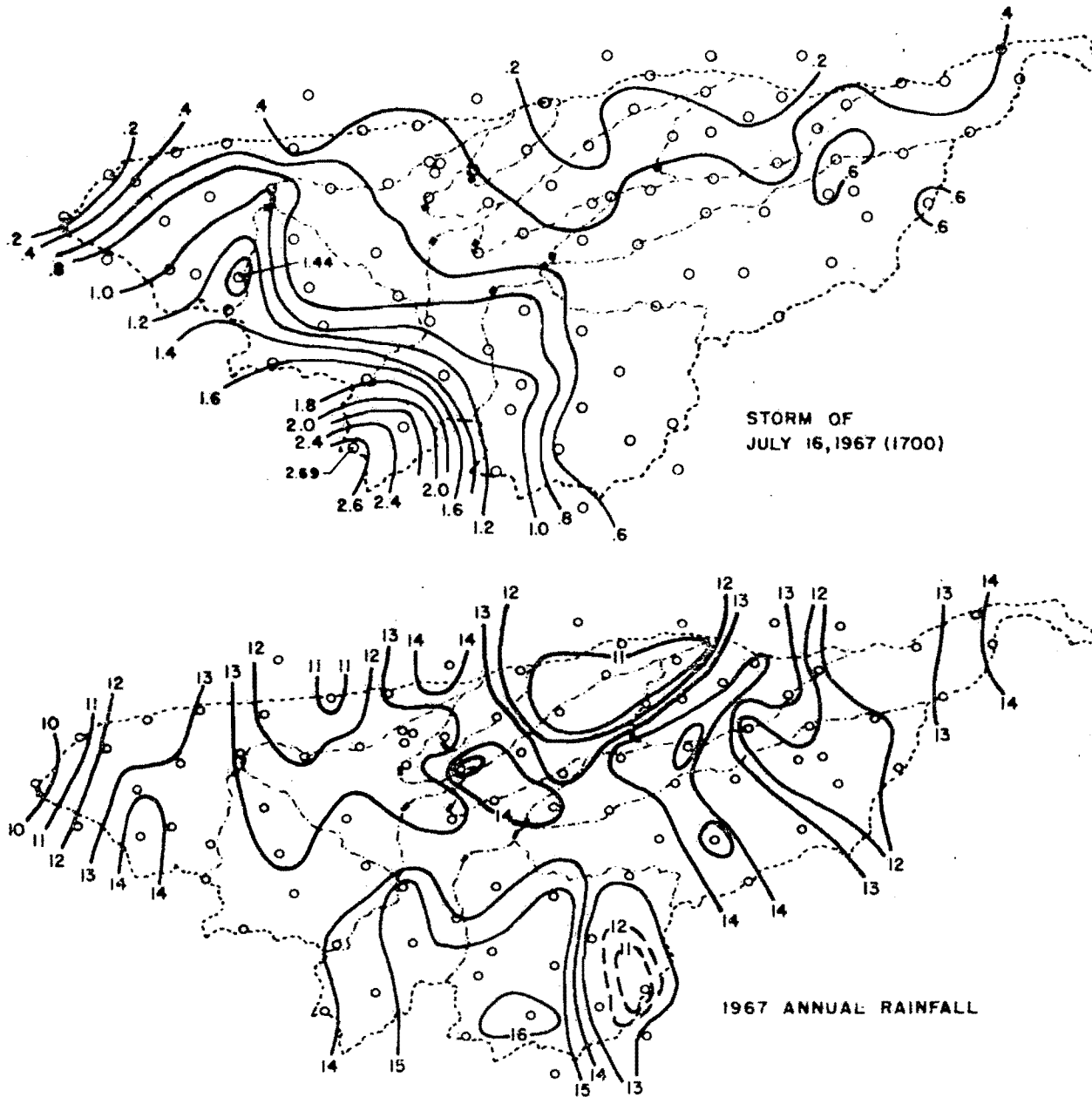


Figure 4. Isohyetal maps of the July 16, 1967, storm, and the annual precipitation (in) for 1967.

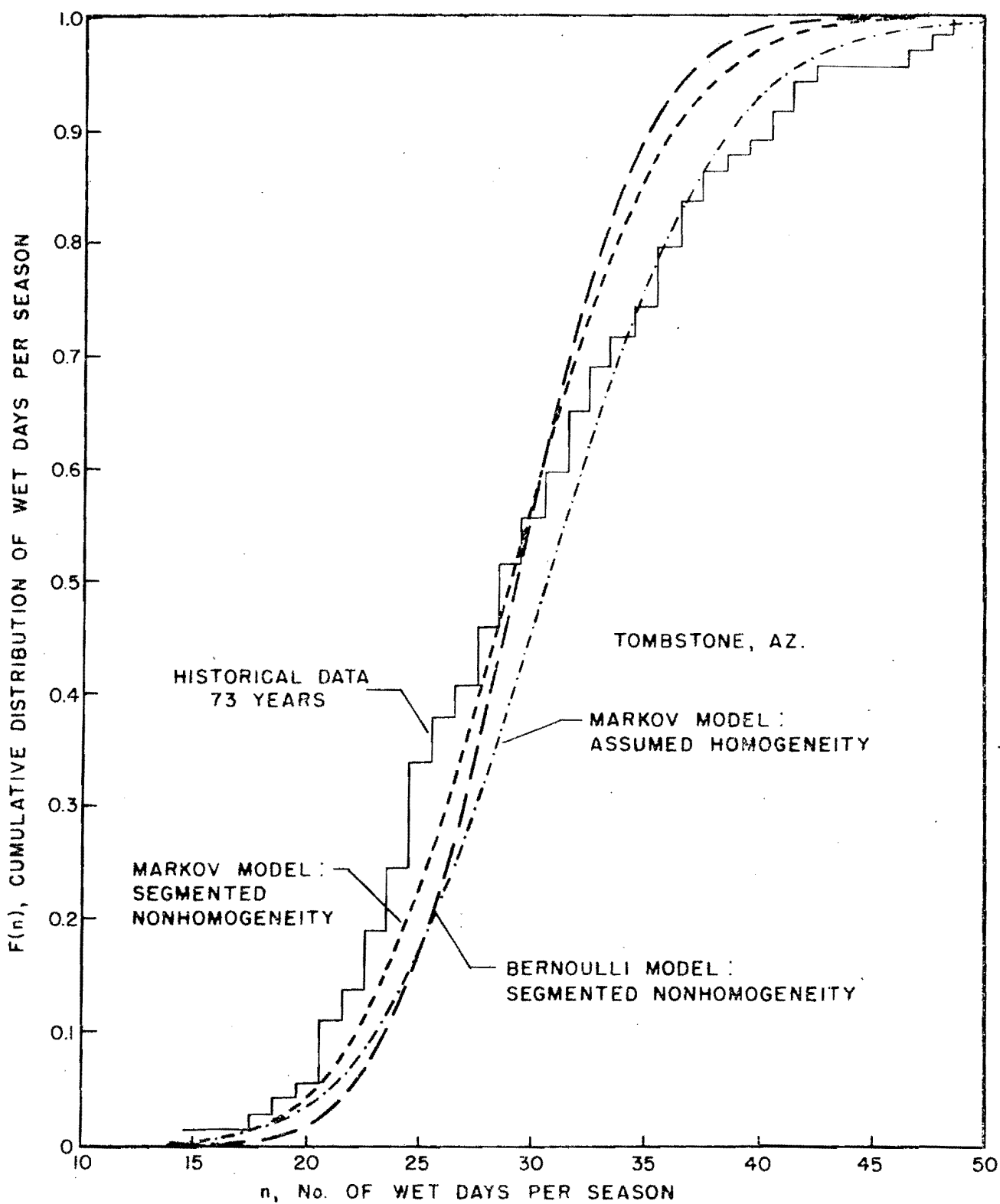


Figure 5. Predicted and observed cumulative distribution of the number of wet days per season at Tombstone, Arizona. (Smith and Schreiber, 1973.)

A distinction should be made between mixed distributions and mixed variables. In mixed distributions, the sample or measurement taken is from describable sources or populations, i.e., storm rainfall or annual flood peaks. For mixed variables, the measurement or sample is taken of components already in a combined state, e.g., streamflow measurement containing surface runoff and groundwater flow.

A two-component mixed distribution as used by Hawkins (1971) was defined as:

$$f(X) = a_1 f_1(X) + a_2 f_2(X) \dots\dots\dots (2)$$

where  $a_1 + a_2 = 1$ ,  $0 < (a_1, a_2) < 1$ , and  $f_1(X)$  and  $f_2(X)$  are normal distribution functions described by  $\mu_1, \sigma_1, \mu_2$ , and  $\sigma_2$ , their means and standard deviations.  $a_1$  and  $a_2$  are the relative weights of each component distribution. The subpopulations are assumed to be normal and have no skewness, although the mixture may, indeed, be skewed.

The probability density function for the two-component mixed normal distribution is thus:

$$f(X) = (a_1/\sigma_1\sqrt{2\pi}) \exp [-(X - \mu_1)^2/2\sigma_1^2] + (a_2/\sigma_2\sqrt{2\pi}) \exp [-(X - \mu_2)^2/2\sigma_2^2] \dots (3)$$

Hawkins (1971) then demonstrated the utility of the mixed distribution model on the maximum 24-hr storm intensity for Farmington Warehouse, Utah (Figure 7). Although this example is not as dramatic as what might be obtained for some runoff stations, the bimodal peak on the density graph illustrates a distribution which is hard to fit with one function. The mixed exponential by Woolhiser (1975) mentioned earlier should also fit this data. Seemingly, further work along this line is warranted, especially since the wide availability of digital computers makes the computations easier.

**Thunderstorm Patterns (Depth-Area Relation)**

Court (1961) presented an early and noteworthy treatment of the description of a thunderstorm's areal pattern comparing the formulas set forth earlier. These efforts at depth-area relations were often peripheral to the main object of investigation. All the relationships reported by Court were empirical (usually obtained graphically) and related the average rainfall inside an isohyet to various powers of the area, or to its logarithm or exponential.

Court (1961) then proposed the bivariate Gaussian (or 'normal') distribution be used as a possible representation of the depth-area relation of storm rainfall. He compared

**Table 1. Daily or shorter precipitation generation models.**

Author	Date	Storm Depth Simulation
Brakensiek	1958	Log-probability and Gumbel extreme value distributions.
Fogel, Duckstein & Sanders	1971	Geometric probability for point depth with a Poisson distribution for the number of rainfall events per season.
Franz	1971	Multivariate normal distribution with persistence provision using a Markov sequence.
Grace & Eagleson	1966	Multi-stage model with storm length selected from a distribution which in turn was related to storm depth.
Khanal & Hamrick	1971	Markov Chain (first-order).
Kotz & Newmann	1963	Gamma distribution.
Nicks	1971	Maximum daily rainfall on a network was a skewed normal distribution with a Markov Chain for occurrence.
Osborn, Lane & Kagan	1971	Complex process using number of cells (Poisson distribution with a three cell minimum) with the center depth approximated by a negative exponential. Separation empirically determined from sample data. Point storm depths are the sum of the depth for all cells.
Pattison	1965	Sixth-order Markov Chain using hourly rainfall states (each state implies a depth range).
Sariahmed	1969	Weibull distribution for storm duration (depth a linear function of duration).
Skees & Shenton	1971	Censored Gamma distribution and numerous transformations to approximate a normal or Gamma shape.
Smith & Schreiber	1973	Mixed exponential distribution for storm depth with Markov Chain for occurrence.
Todorovic & Woolhiser	1971	Exponential for daily rainfall with the total amount of precipitation in an N-day period from a Markov Chain or a binomial distribution.
Wiser	1971	Mixed distribution generated from: 1) a storminess parameter (second-order autoregressive scheme) and 2) local process deterministic component (e.g., orographic effects) with a random selection that determines the simulated precipitation.

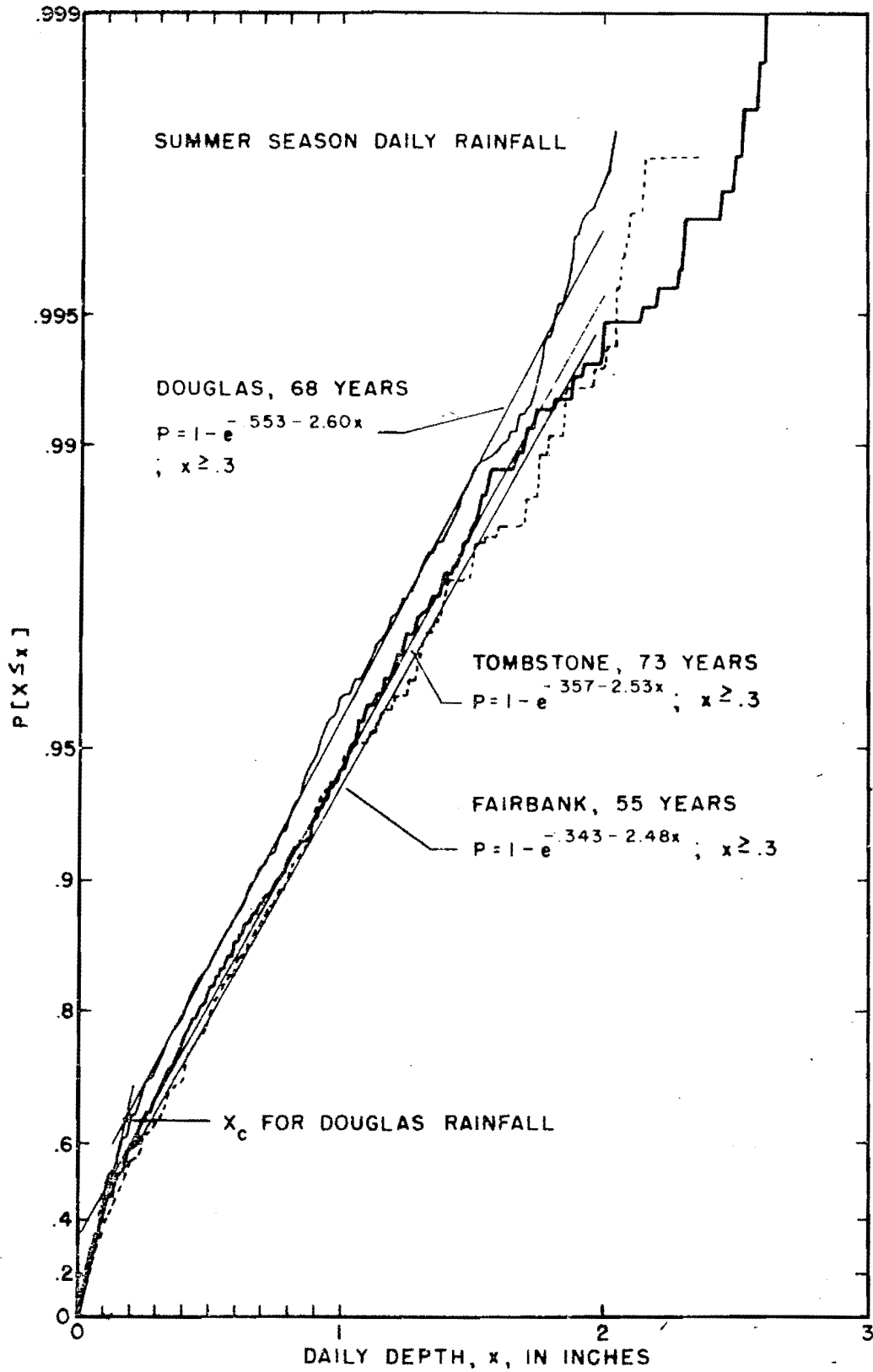


Figure 6. Distributions of summer seasonal daily rainfall depths for three sampling stations in southeastern Arizona. (Smith and Schreiber, 1974.) (in  $x \ 2.54 = \text{cm}$ )

his Gaussian (normal) model with that of other investigators as shown in Figure 8.

Interestingly, the models reflect the differing storm patterns studied from the limited extent air-mass storms described by Woolhiser and Schwalen (1959) in Arizona to the broad expanse storms of Huff and Stout (1952) in Illinois.

Recently, Smith (1974) investigated the areal properties of thunderstorms in Arizona and described the storm

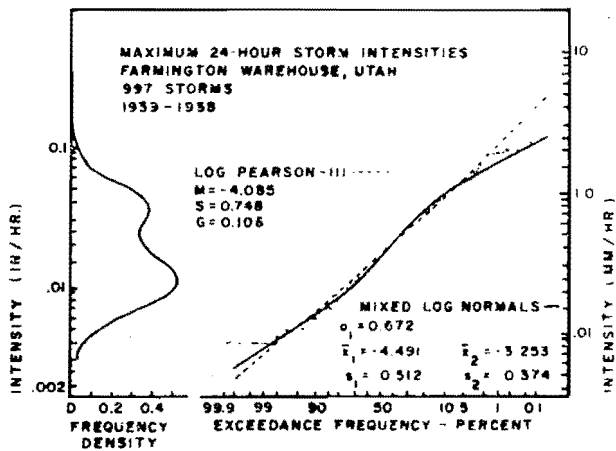


Figure 7. Frequency curves for precipitation data, comparing mixed normal distributions to Pearson-III distributions. (Hawkins, 1971.) (in/hr x 2.54 = cm/hr.)

pattern with a monotonic dimensionless depth-area relationship. He also expressed the depth-area relations for air-mass thunderstorms proposed by three other investigators in dimensionless form as shown in Figure 9. Assuming storms are occurring randomly, uniformly distributed in space, the rainfall population at any point may be considered to be composed of samples taken with equal likelihood from any point within the associated storm. With probability statistics he developed from this assumption, a general relation was presented between normalized storm isohyetal pattern, center depth probability, and point rainfall probability. This general relationship and the dimensionless depth-area relationships were used to obtain a record of the point rainfall depths which compared quite favorably with the historical record at the Tombstone rain gage (Figure 10).

### INTERIOR NORTHWEST RANGELAND PRECIPITATION

Rangeland areas in the interior Northwest have maritime air from the Pacific Ocean as their moisture source for precipitation. The maritime influence is particularly noticeable during the winter, with greater average cloudiness, greater frequency of precipitation, and mean temperatures which are above those at the same latitudes east of the continental divide. The north-south mountains which dominate the Northwest result in a high percentage of the maritime moisture falling on western slopes, whereas the area east of these mountains receives only small amounts of precipitation. The sum result is an almost typical upland continental climate in summer, but

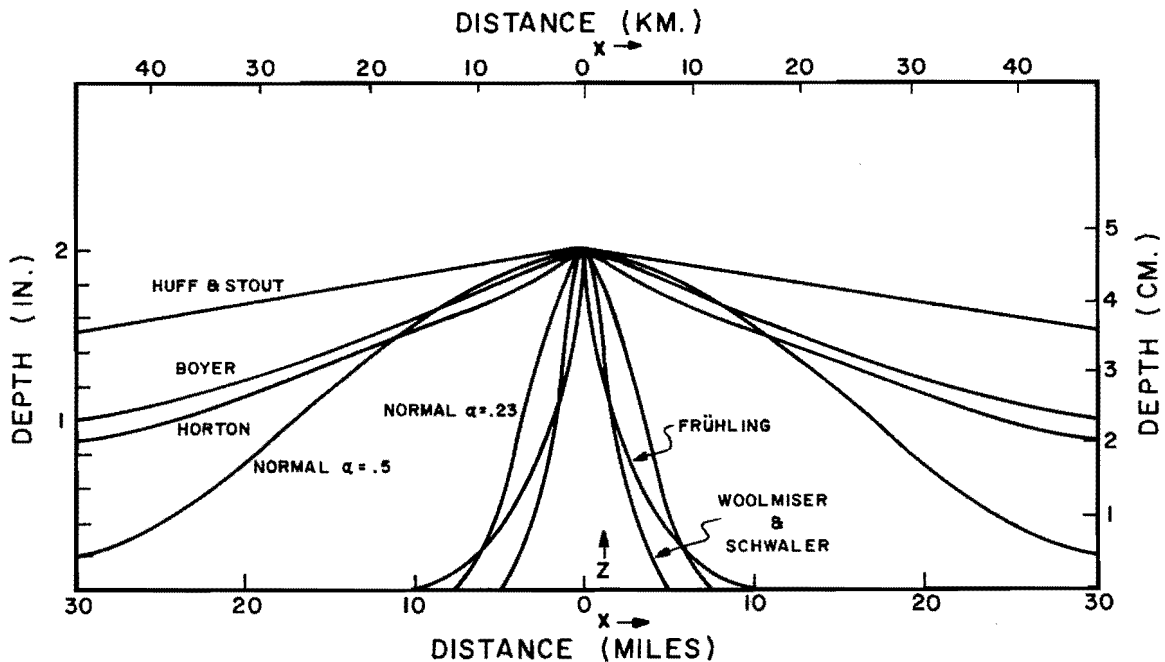


Figure 8. Variation of isohyetal value  $z$  (in) with distance  $x$  (mi) from storm center, assuming central precipitation to be  $m = 2$  in (5.08 cm), according to various formulas. (Court, 1961.)

one tempered by periods of cloudy or stormy and mild weather nearly every winter. The normal precipitation in the Boise, Idaho, area shows a winter maximum and a very pronounced summer minimum (Figure 1). Within the interior Northwest region, elevation is the primary cause of great differences in precipitation over very short distances.

Annual precipitation on the Reynolds Creek Watershed, operated by the USDA, ARS, Northwest Watershed Research Center, varied from 254 mm (10 in) at the lower elevation of 1097 m (3600 ft) to near 1270 mm (50 in) at the highest elevation near 2134 m (7000 ft). Figure 11 shows the monthly distribution at three elevation sites in the watershed. Figure 12 shows the spatial distribution of annual precipitation over the watershed.

Even though winter precipitation predominates in the Reynolds Creek rangeland watershed, there are summer thunderstorms. However, they are very infrequent and

since the previous discussion in this paper has covered them thoroughly, thunderstorm precipitation will not be discussed further.

**Low Elevation Winter Precipitation**

At the lower elevations, less than 1524 m (5000 ft), winter precipitation comes as both rain and snow. At these elevations, the most severe floods come between December and March (Johnson and McArthur, 1973). The usual antecedent conditions are persistent periods of extreme cold, which freeze the soil to considerable depth, and a shallow snow cover. Warm, moist, unstable air masses, accompanied by strong southwest winds, produce rain and cause rapid melting of the snow on frozen ground. The amount and intensity of the rainfall, the amount of snowmelt, and the imperviousness of the frozen soil combined to affect the flood severity.

Because the snow cover and soil frost depths at lower elevations change from day to day, devising a data

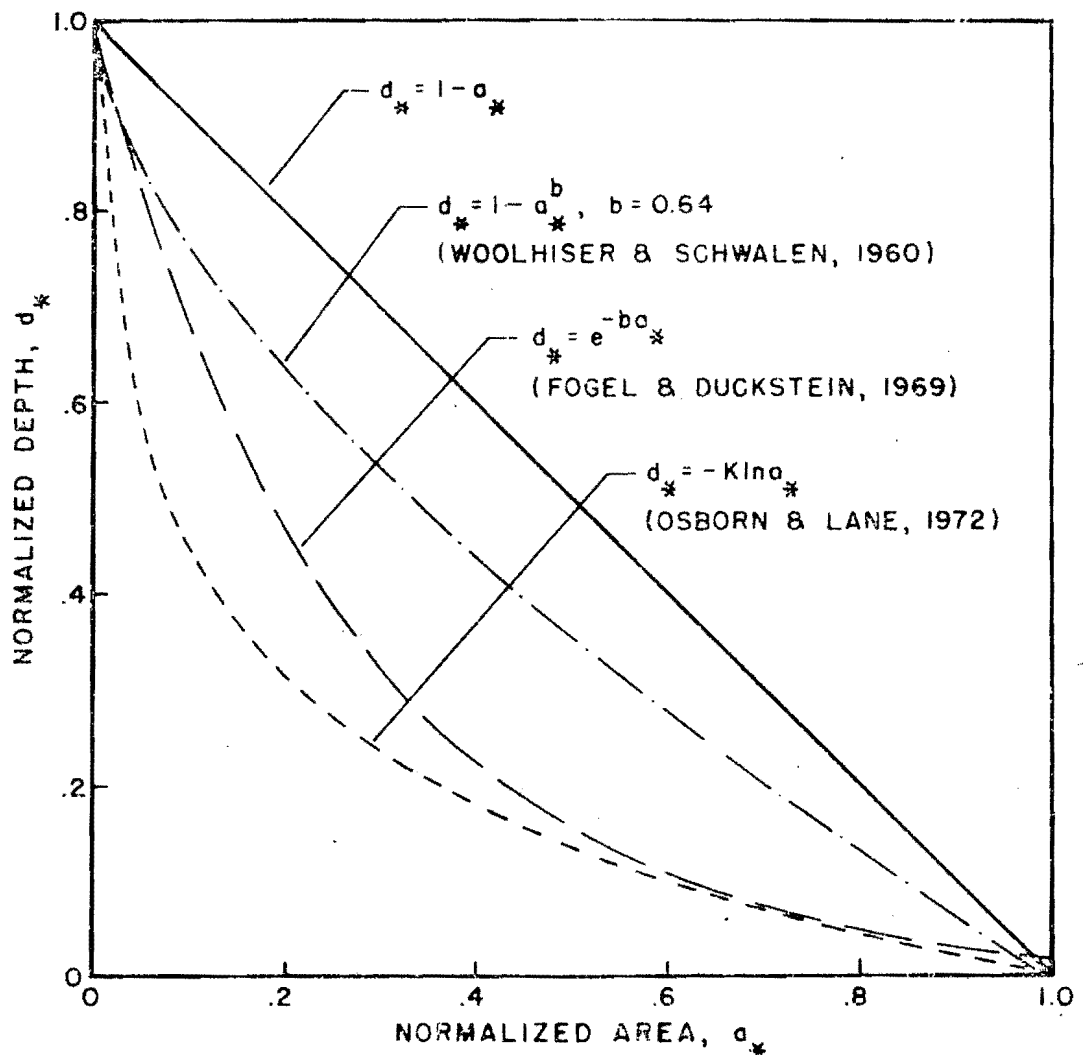


Figure 9. Normalized depth-area relations for air-mass thunderstorms proposed by three investigators. (Smith, 1974.)

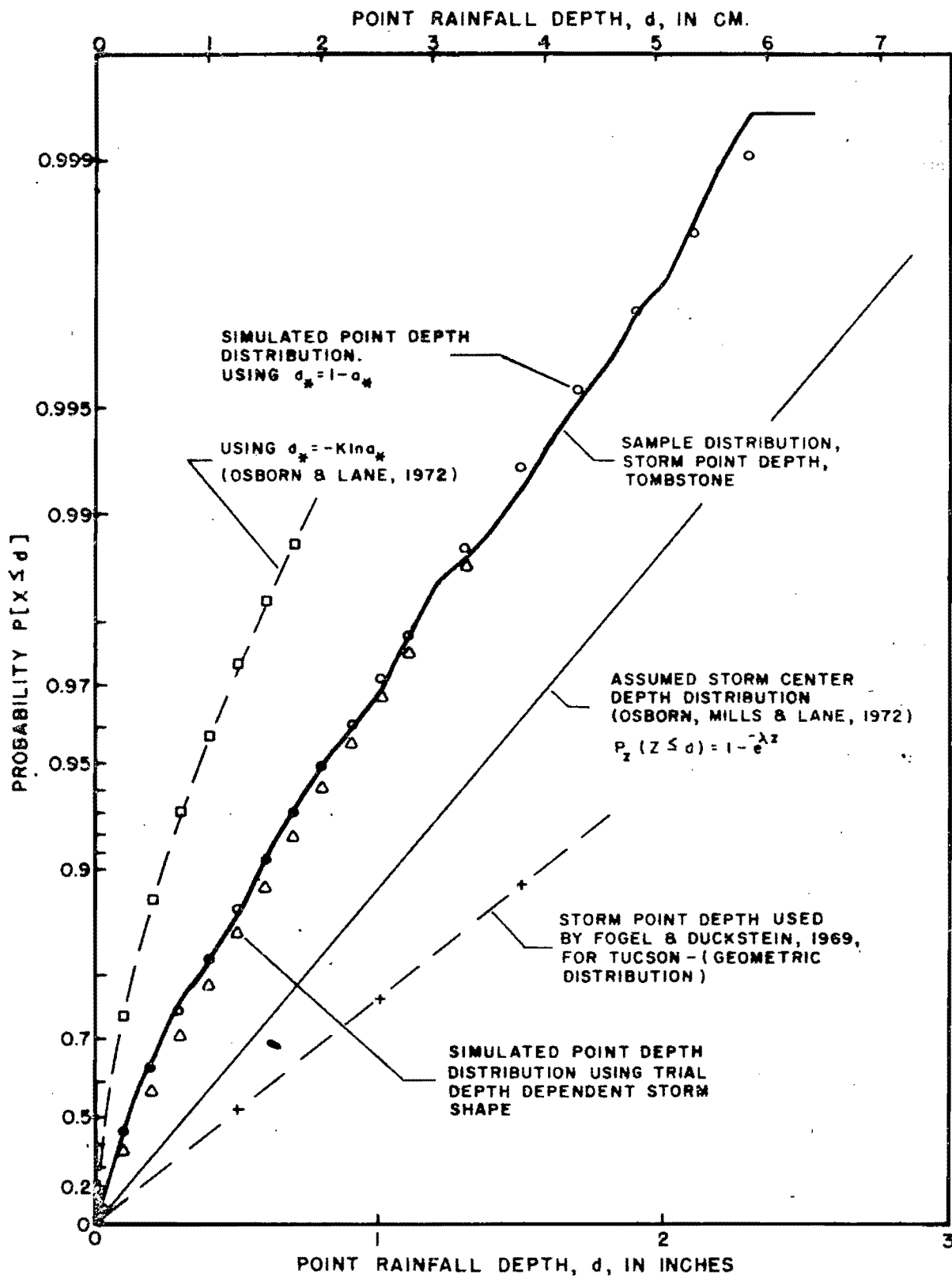


Figure 10. Storm center-depth distribution and several point depth distributions, including measured data for Tombstone, Arizona, and simulated distributions. (Smith, 1974.) (in  $\times 2.54 = \text{cm.}$ )



collection network to provide a historical record and research data of antecedent conditions before a snowmelt-runoff event has been necessary. Such a data collection network was initiated on the Reynolds Creek Watershed during the 1971 to 1972 winter season. Data collected includes general snowline elevation, snow depths, snow-water equivalent, percent of snow cover, soil frost depth, and existing weather conditions. This data is being used to study snowmelt-runoff relationships at the lower elevations. Much of this water runs off rather than infiltrates the soil. Nonetheless, winter precipitation does recharge shallow water supplies that are utilized for stockwater tanks. In those areas of a deep soil profile, furrowing may be used to retain some surface runoff for soil infiltration. Such additional water harvested and infiltrated may prove crucial in these areas for establishing a more productive range. These areas are now used only in early spring and the principle forage is cheatgrass (*Bromus tectorum*).

However, research is needed to evaluate this complex relation between winter stored soil water, negligible summer rainfall, and grass varieties that are adapted to the soil and water conditions.

**Mid and High Elevation Winter Precipitation**

At mid-elevation, 1500 to 2100 m (5000 to 7000 ft), precipitation comes as snow and is stored on the watershed until spring melt. Approximately 75 percent of the annual water yield from Reynolds Creek is from snowmelt. Discontinuous snow storage as massive drifts is prevalent on the watershed, which is typical of many millions of hectares of medium elevation sagebrush rangeland in the northwest. Research on the Reynolds Creek Watershed has quantified the magnitude of this water resource and has identified possible ways to manage this resource for

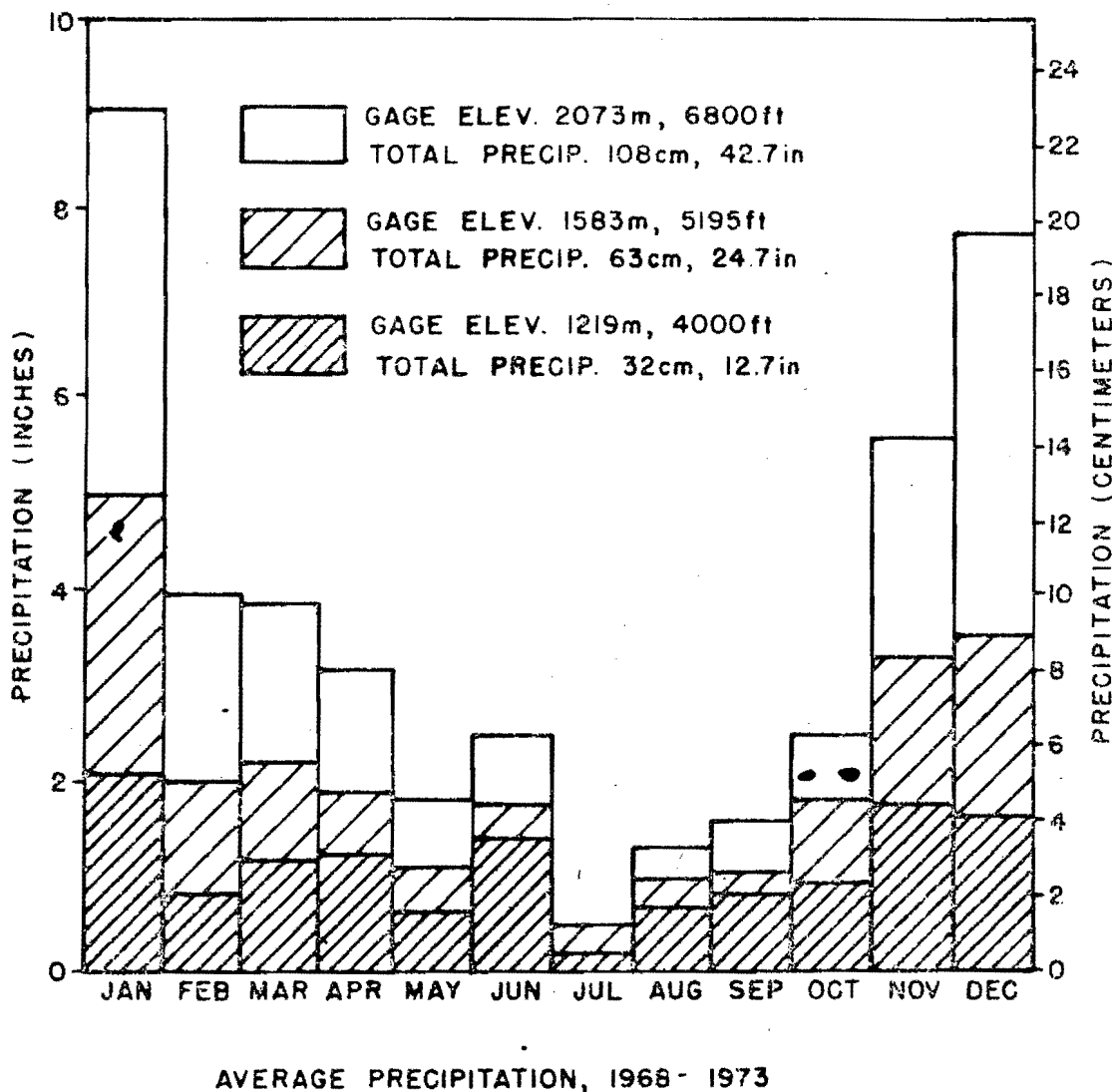


Figure 11. Reynolds Creek Watershed, Idaho. Average precipitation for 1968 to 1973.

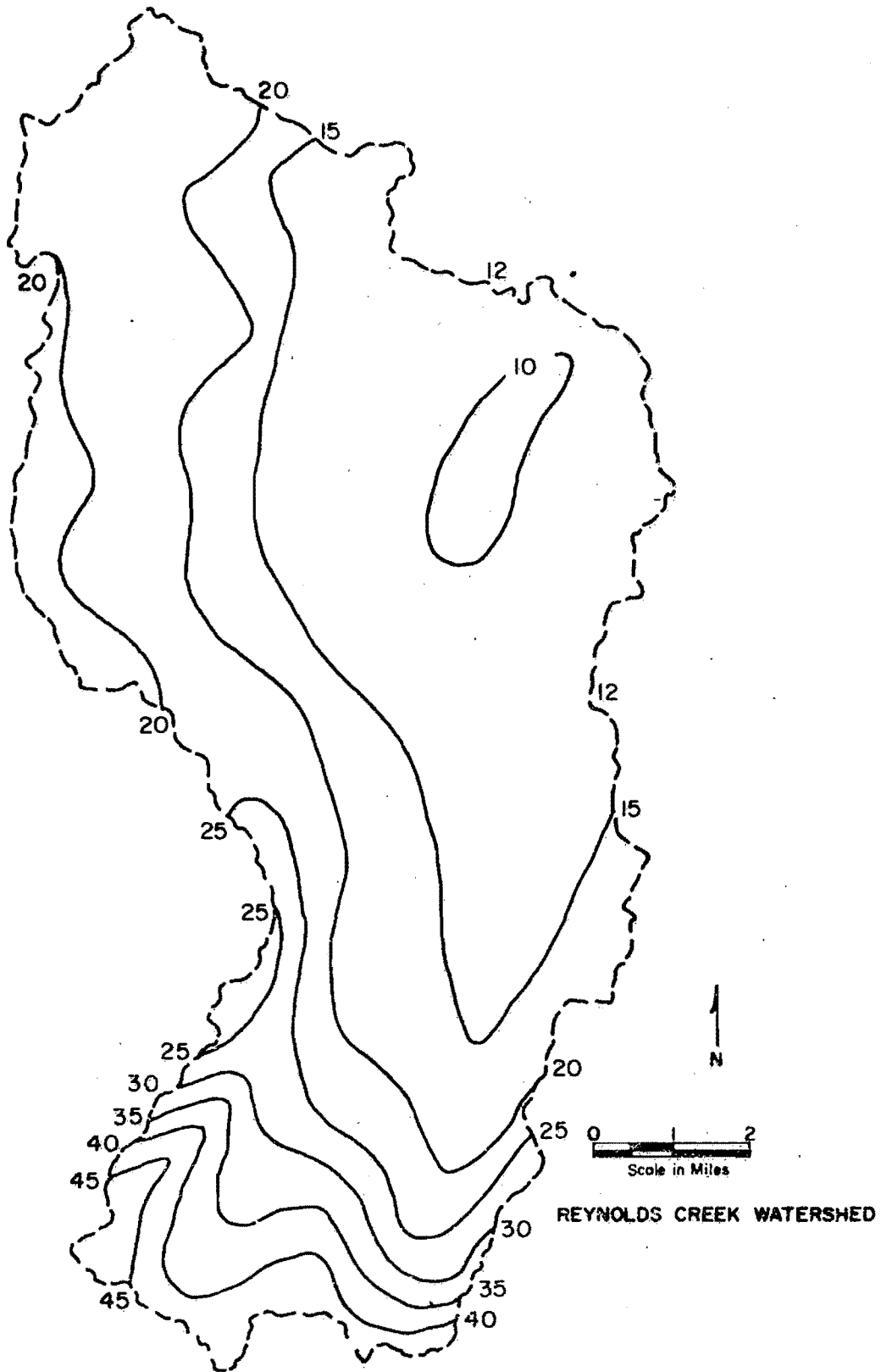


Figure 12. Annual rainfall [inches] at Reynolds Creek Watershed, Idaho.

more efficient use. The following section will discuss these natural systems, their measurements, and potential management.

**Physical System**

Snow, as it falls and where it initially settles, is moved and redeposited by an interaction of wind with topography, vegetation, and elevation. By the start of the melt season,

the yearly areal distribution of snow is roughly the same regardless of the total snow volume that fell. This snow cover is present as large, isolated snowdrifts, located on north- and east-facing slopes which persist late into the melt season, with some remnants remaining even into late July and early August (Figures 13 and 14).

Many of these snow accumulation slopes are covered with a deep soil, and thus, in combination with the soil



Figure 13. Snowdrift sites, 6/10/74.



Figure 14. Segment of Figure 13 on 6/10/74. Lower fringes up to trees contains  $28.400 \text{ m}^3$  (28 ac-ft) of water.

water supply, could be managed as high forage production sites. Approximately 30 percent (54 km<sup>2</sup> (21 mi<sup>2</sup>)) of the mid-elevation part of the watershed are comprised of north- and east-facing slopes which presently are mostly aspen or sage brush covered.

#### Measurement by a Dual Gage System

Much has been written about errors in the catch of recording rain gages. Court (1960) stated that the largest source of error connected with raingage readings lies in the assumption that they represent the actual precipitation at the site. Several investigators have found that rain gages normally exposed with level orifices and placed approximately 1 m (3 ft) above the ground surface caught from 3 to 10 percent less rain than did a gage with the orifice at the ground. Individual storm or daily amounts could be as great as 50 percent (in windy situations) in error. Neff (1975) made similar comparisons for several locations in the Western U.S. and his results are summarized in Table 2.

The Reynolds Creek precipitation network consists of 46 dual-gage sites, (1 site/5.18 km<sup>2</sup> (1 site/2 mi<sup>2</sup>)). Each is instrumented with two recording raingages, mounted on posts, with the collectors at 3.04 m (10 ft). One of the gages is shielded by a modified Alter shield, with the baffels constrained at 30 degrees from vertical to maintain a constant airflow across the collector. The second gage is unshielded.

The purpose of the dual-gage network is to develop a procedure for calculating "true" precipitation, especially in areas of snowfall, since the combination of wind and snow is the major source of error in gage catches. The method used at Reynolds Creek for computing "true" precipitation was developed by Hamon (1972), and requires the unshielded gage catch, shielded gage catch, and an empirically determined calibration coefficient as input parameters.

#### Measurement by Photogrammetry

Measuring snow depths and the areal distribution of snow by aerial photogrammetry on the 40 hectares (16.2 ac) subwatershed in the Reynolds Creek Experimental Watershed was shown as a practical method for obtaining

detailed information on the distribution of snow in areas of complex relief (Cooper, 1965).

Briefly, the photogrammetric method for measuring snow consists of initially making a topographic map of the area and establishing horizontal and vertical controls at specified points. Then, at the desired intervals during the snow season, the control stations are remarked, the snow depth measured at each of the control stations, and the area rephotographed aurally to determine snow elevations where volume is computed. Although the snow depth and volume over an area may be accurately determined by this method, considerable error could be introduced when calculating the total water content of the snow cover because of the variation in snow density over the study basin.

Continued study of photogrammetric snow measurements on the Reynolds Mountain Study Basin have indicated that grid spacing could be increased from 7.6 m to 30 m or 100 m (25 to 100 or 325 ft) with only a 2.5- and 10-percent loss of accuracy in total volume of snow, respectively. The above change in grid spacing enabled the number of points processed to be decreased by 94 and 99 percent, respectively. Continued evaluation of snow density on the watershed has indicated that density varies according to aspect and drift locations. Some drift locations may have snow density 10 percent greater than some other sites.

#### Snowmelt Studies

The rate at which a snowpack will melt is dependent on the amount of heat it receives from three sources: 1) radiant heat from the sun, 2) latent heat of vaporization from the condensation of water vapor on the snow surface, and 3) heat by conduction from the ground, rainfall, or air in contact with the snow. The snowmelt process can be very complex because heat may be added to the snowpack by any or all of these sources, or the snowpack may be simultaneously gaining heat by one process and losing it by another. Actual snowpack melt is produced by a combination of all heat sources. Under different meteorological conditions, different heat sources will predominate in producing melt.

An early May 1972 study, when most of the ground surface was covered with snow, showed that net radiation supplied about 82 percent of the melt energy, with the

**Table 2. Precipitation catch in ground level and 3 ft high orifice rain gages (from Neff, 1975).**

Location	Type of Gage	Average Error	Range in Error
Reynolds Creek, ID	Belfort Recording	7%	0-50%
Pullman, WA	U.S. Weather Bureau Standard nonrecording	10%	0-50%
Ekalaka, MT	Fischer & Porter Recording	18%	0-75%
Sidney, MT	Fischer & Porter Recording	4%	0-50%

remaining 18 percent lost by evaporation. However, during the latter part of June, when only isolated snowdrifts were present, net radiation supplied 60 percent of the melt energy, sensible heat exchange accounted for 32 percent, and about 8 percent vapor exchange was recorded.

Exceptionally high snow ablation rates were measured on an isolated, late-lying snowdrift during May and June, 1974. Unseasonably high, average daily air temperatures, 16° C (61° F), were recorded at the 2072 m (6798 ft) elevation during late May and June and, thus, contributed to this high ablation rate. For one 9-day period during the latter part of June, 7.1 cm (2.8 in) of water were melted and 3.3 cm (1.3 in) were evaporated for a total loss of 10.4 cm/day (4.1 in/day). Energy exchange measurements showed that 54 percent of the energy available for ablation came from sensible heat transfer and 46 percent from radiant heat. This is contrasted with continuous snow cover conditions where practically all of the energy comes from radiant heat transfer. Drift profile studies showed that the top of the drift surface ablated 23 percent faster than the more abrupt face.

**Snowmelt Forecasting**

For a forecast model to be analogous to a simplified water balance equation, each coefficient must have hydrologic significance. To achieve this, each beta coefficient should represent a percentage of the total drainage area. The terms  $\beta_1 X_1 \dots \beta_n X_n$  in the forecast equation are analogous to a weighted average scheme and can then be expressed as

$$Y = a + \sum_{i=1}^n (\beta_i) (X_i) \dots \dots \dots (4)$$

The hydrologic significance of  $\beta_i$  can be maintained by the additional requirements that  $\beta_i \geq 0$  and  $\sum_{i=1}^n \beta_i \leq 1$ .

provided that runoff and snow-water contents are expressed in the same units, (e.g. cm or in). The basis for this reasoning is that the snow-water content at a snow course is considered as a discrete sample of snow water content associated with an area within a drainage basin, and not simply as an index of runoff.

A general optimization program developed by TVA (Green, 1970) was used to generate beta coefficients and alpha values of Equation (4) for various forecast periods for three drainage basins located in southwest Idaho: Tollgate Drainage of Reynolds Creek Watershed, the Middle Fork of the Boise River, and the entire Boise River above Boise, Idaho (Zuzel, Robertson, and Rawls, 1975).

To verify the usefulness and accuracy of the forecast procedure, an optimized March-July forecast equation was developed for the Tollgate Drainage of the Reynolds Creek Watershed, using 7 years of record from seven snow courses (1966 to 1972). The forecast equation was first solved for the fitting coefficient, alpha, using Thiessen weights as the beta coefficients. The solution resulted in a correlation coefficient (r) of 0.979 and a standard error of 1.93 cm (0.76 in) or 9 percent. The equation was then solved to optimize coefficients by using the Thiessen weights as initial estimates of the beta coefficients. The initial estimate of alpha was obtained from the Thiessen solution. Optimization resulted in a correlation coefficient (r) of 0.993 and a standard error of estimate of 1.12 cm (0.44 in) or 5 percent. Table 3 compares the coefficients and results of the Thiessen and optimized forecast equations. The optimization process eliminates snow courses that do not contribute to the forecast accuracy by assigning a weight of zero to them.

Additional progress is being made to improve forecast equations for short time periods of the snowmelt process; a better understanding of the relative importance of various meteorological parameters is needed. Factor analysis and regression analysis were used to determine the effectiveness of wind, air temperature, vapor pressure, and net radiation in predicting snowmelt (Zuzel and Cox, 1975).

**Table 3. Tollgate drainage 54 km<sup>2</sup> (21 mi<sup>2</sup>). March-July Forecast, developed from 1966-1972 data.**

Snow Course	Thiessen Weighted	Optimum Weighted
144062	0.1881	0.2207
155054	0.1876	0.1936
163020	0.0424	0.1425
163098	0.0581	0.0
167007	0.1471	0.0
174026	0.0352	0.0861
176007	0.0786	0.0
Correlation Coeff.	0.978	0.993
Fitting Coeff.	-0.07	-9.53
Error Range -	2% - 16%	1% - 17%
Standard Error	1.93 cm (9%)	1.2 cm (5%)
Average Runoff	20.47 cm	20.47 cm

Analyses of meteorological and snowmelt data collected at the Trinity Mountains in the Boise River basin in May 1973, showed that the standard error of daily snowmelt prediction could be decreased 13 percent by using vapor pressure, net radiation, and wind in predictive equations rather than just air temperature (Table 4).

#### Management of Rangeland Snow

Management of snowdrift shape by natural barriers or fences could, by reducing the flat top and increasing the slope, significantly reduce evaporation losses. Because air-borne particles have very high sublimation losses, barriers would reduce these losses by tying down the snow particles. An optimum shape of the drift would also prolong melt into the summer season, and extend soil water supplies and water yield to streams.

A trial planting of Monterey Knob Cone Pine trees was made at one drift site to test the possibility of using natural vegetation for snow management purposes. Two hundred trees were planted in two rows, .61 m (2 ft) apart at the toe of an existing snowdrift in the center of a mile-long drift area. Approximately 55 percent of the trees have survived to date.

Melt from the drifts not only provides most of the dependable water yields from watersheds, like Reynolds Creek, but also furnishes soil water to deep soil laid slopes. Nonproductive vegetation now uses this water. A real

potential exists for increasing the productivity of these areas by modulating snowmelt.

#### CONCLUDING COMMENTS

The range scientist is undoubtedly interested in the soil water available for forage production, which a hydrologist should be able to forecast from available precipitation data. Much of the historical work of hydrologists pertaining to precipitation was intended for estimating streamflow. The analytic tools developed in this work are available to range scientists and should facilitate estimating the water available for forage.

Precipitation variability is large in basin and range physiographic areas as well as in major mountain areas like those in most range areas of the Western U.S. Orographic precipitation patterns, redistribution of blowing snow and thunderstorms of limited areal extent, all contribute to the steep isohyetal gradients and limit the application of rain-gage data, except for the point in question. Unfortunately, additional gages are greatly needed at sites removed from the valley floors to facilitate quantifying the variability. The thunderstorm phenomenon which dominates the rainfall pattern in much of Arizona and New Mexico, also exists in other portions of the Western U.S. and produce the extremely large runoff events on small watersheds, which might be used for stock watering ponds. Additional rain gage network data are needed to supplement the information from the three large networks presently in operation in the Western U.S (Walnut Gulch in Arizona, Alamogordo Creek in New Mexico, and Reynolds Creek in Idaho). Also needed is a more concerted effort by hydrologists to translate hydrologic modeling outputs to soil water availability for forage production.

Future hydrologic research and application will probably lead to developing maps of the areal variation in values of transition probability, and values of  $a$ ,  $\lambda$  in the daily depth distribution as discussed. These parameters can be described successfully through the year with a Fourier series (only a few terms are needed), thus producing a space and time model of precipitation. Such information should be more comprehensively valuable than the currently used maps of various depths and probabilities for specified storm durations.

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**Table 4. Correlation of meteorological factors with snowmelt, Trinity Mountain, Idaho.**

Independent Variables	R	Standard Error (cm) <sup>1</sup>	Standard Error (%)
VP, NR, W	0.885	1.00	30
VP, NR, W, T	0.885	1.02	31
VP, NR	0.823	1.18	35
W, T, NR	0.827	1.20	36
T, VP, NR	0.824	1.21	36
W, T, VP	0.788	1.31	39
W, T	0.773	1.32	40
T, NR	0.773	1.32	40
T, VP	0.728	1.43	43
W, VP	0.720	1.45	43
W, NR	0.718	1.45	43
T	0.717	1.42	43
NR	0.631	1.58	47
VP	0.628	1.59	48
W	0.383	1.88	56

W = 24-hour wind run (km)

T = Average 24-hr air temperature (°C)

VP = Average 24-hr vapor pressure of air (mmbar)

NR = 24-hr net radiation (Ly)

R = Multiple Correlation Coefficient

NUMBER OF OBSERVATIONS for each analysis = 24

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# Percolation and Streamflow in Range and Forest Lands

Alden R. Hibbert\*

## INTRODUCTION

Some two-thirds of the total land surface of the earth can be classified as forest or range. Simply stated, forest is an area dominated by trees, while range is an area where the natural vegetation is predominantly grasses, forbs, and shrubs. There are important differences in surface and subsurface hydrology in these areas that stem largely from differences in climate, soils, and topography. Arid lands support sparse vegetation, soils tend to be shallow and poorly developed, and water seldom percolates beyond the rooting depth of plants. On the other hand, humid areas are usually well vegetated, soils are deeper and better developed, and water consistently percolates beyond plant roots to feed streams and groundwater. Water yield from forests is relatively high—not because of the trees, but in spite of them—whereas the warmer, drier ranges yield less water and more sediment.

Plant growth and maintenance of streams and groundwater depend upon precipitation getting into the soil. On most well-vegetated soils, virtually all rain and snowmelt soak in; even on desert soils, the proportion of total precipitation that runs off the surface is small. Under very intense rainfall, however, even a small percentage of the rain flowing away over the surface can do tremendous damage. Therefore, surface runoff is usually considered undesirable. It should be promoted, as in water harvesting, only when the risks of erosion and flood damage are low.

I will discuss in a general way the movement of water into and through soils. It is impossible to treat this subject in detail in the allotted time, so I will concentrate on certain aspects of soil-water and groundwater relations that seem pertinent to management of soil and water resources in forest and range lands.

## INFILTRATION AND PERCOLATION

Infiltration is one of the most critical processes in hydrology. It is defined as the entry of water into the soil.

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Just when infiltration ends and percolation begins is not clear, but most authorities visualize water passage through the mineral soil surface as infiltration, and further downward movement as percolation. In reality, water movement into and through soils is a continuing process, beginning with the advent of rainfall and not ending for days or even months.

Horton (1933) is generally credited with the modern development of the infiltration concept. During the 1930's and 40's, Horton and his coworkers firmly established the role of infiltration in the runoff process. Perhaps the most critical assessment of the Hortonian concept is that too much emphasis was placed on the portion of rain that failed to infiltrate, and not enough on the part that soaked in. It is easy to see why surface runoff received so much attention in the early part of this century. Western and Eastern ranges alike were being overgrazed, some severely. Farming practices included few conservation measures, and little was being done to rehabilitate cutover lands. The drought of the 1930's further stressed the land, and rains that formerly would have soaked harmlessly into the soil, began to run off in torrents.

## The Infiltration Process

Many factors affect the movement of water into soil. In simple terms, water enters the soil when the driving force (lower branch Figure 1) is greater than resistance to wetting and movement of water (upper branch Figure 1). Normally, water is strongly adsorbed to soil particles by capillary action. The downward vertical component of this force plus gravity constitute the major driving force. However, if the soil particles repel rather than attract water, the net driving force may be negative and external hydraulic pressure is necessary to overcome surface tension and force water through the voids between soil particles. When soil freezes, passageways may be blocked if the frozen surface layer contains much water (Gray et al., 1969).

If the soil is wettable and dry, the first water enters rapidly under strong capillary action. As the process continues, flow paths lengthen between the surface and the wetting front, and the resistance to flow increases. At the same time there may be a decrease in porosity at the

surface caused by pores sealing with inwash of finer particles and swelling of clay and colloids. Water may collect on the surface and flow freely into the soil through relatively large voids or channels formed by shrinkage cracks, roots, and animals. Here, also, effectiveness of the cracks in particular decreases as swelling action closes them.

These inhibiting factors result in a rapid reduction of infiltration rate during the first minutes or hours of rainfall (Figure 2). The rate levels off and remains relatively constant as long as water application continues at a rate equal to or greater than the infiltration rate. If rainfall intensity is variable or intermittent, some recovery in the infiltration rate will occur as the soil drains between periods of rapid input.

Water moves into soils according to definite laws that can be expressed mathematically. According to Taylor (1961), when water infiltrates an initially dry uniform soil under natural conditions, the amount of water,  $Q$ , that will infiltrate a soil of unlimited extent increases in proportion,

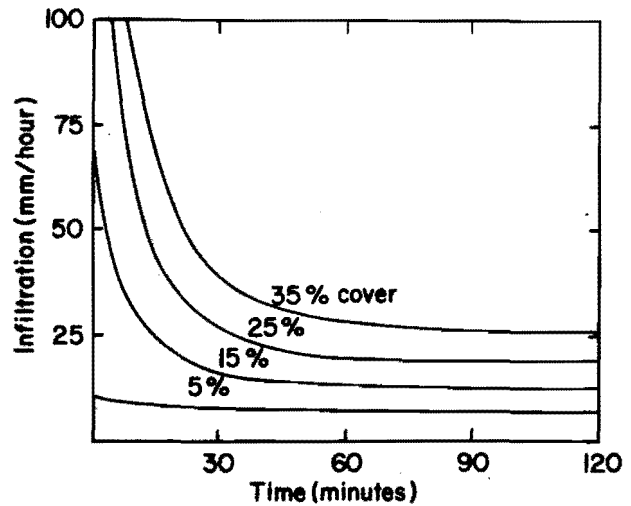
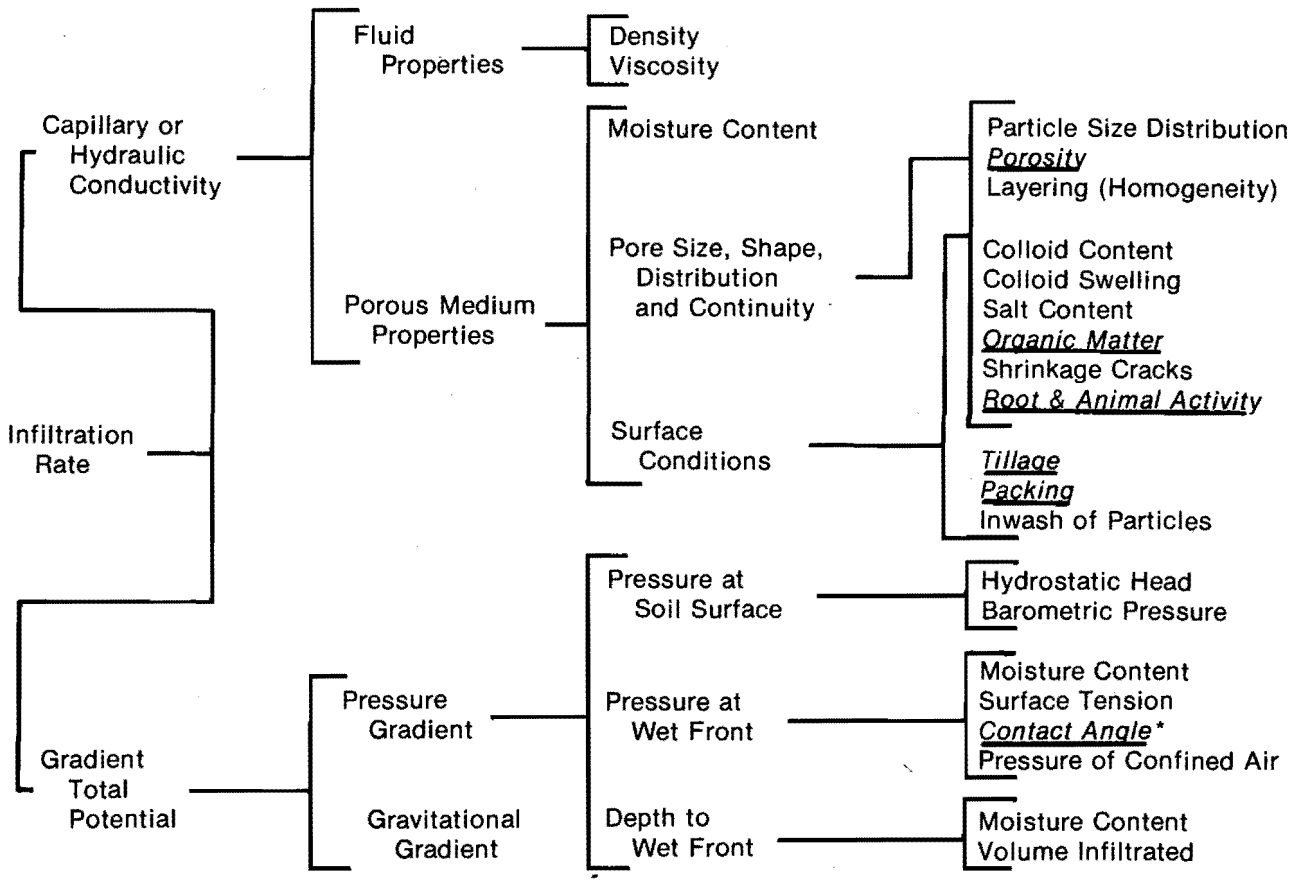


Figure 2. Average rate of infiltration curves for limestone soil under four densities of herbaceous cover, Sevier Lake watershed, Utah (after Woodward 1943).



\*Wettability

Figure 1. Factors affecting infiltration of rain into unfrozen soil (after Gray, Norum, and Murray 1969). Resistance to movement of water through porous media is affected by factors shown in the upper branch; the lower branch depicts driving forces and factors affecting them.

c, to a power exponent, a, of time, t.

$$Q = ct^a \dots\dots\dots (1)$$

(Note that Q is the cumulative amount infiltrated after a given time, not an instantaneous rate.) If the soil is homogeneous, the exponent, a, is 1/2, according to theory. However, if water reacts with the soil system by causing it to swell or change size, then the exponent of time is different as can be seen in Figure 3 (a plot of log Q vs. log t): the slope of the line, a, is different for four different soils.

If water enters rapidly at first but slowly after an hour or so of soaking, such as in a soil that cracks and swells, then the exponent, a, is a low number. Houston clay is such a soil. Cecil clay loam has low infiltration throughout. Millville silt loam starts at an intermediate rate but holds up well. The most water is absorbed by Honeyoye gravelly silt loam, the least by the clay soils. Measurements of infiltration rates in the field indicate that the exponent, a, ranges between 0.1 and 0.8 (Taylor, 1961).

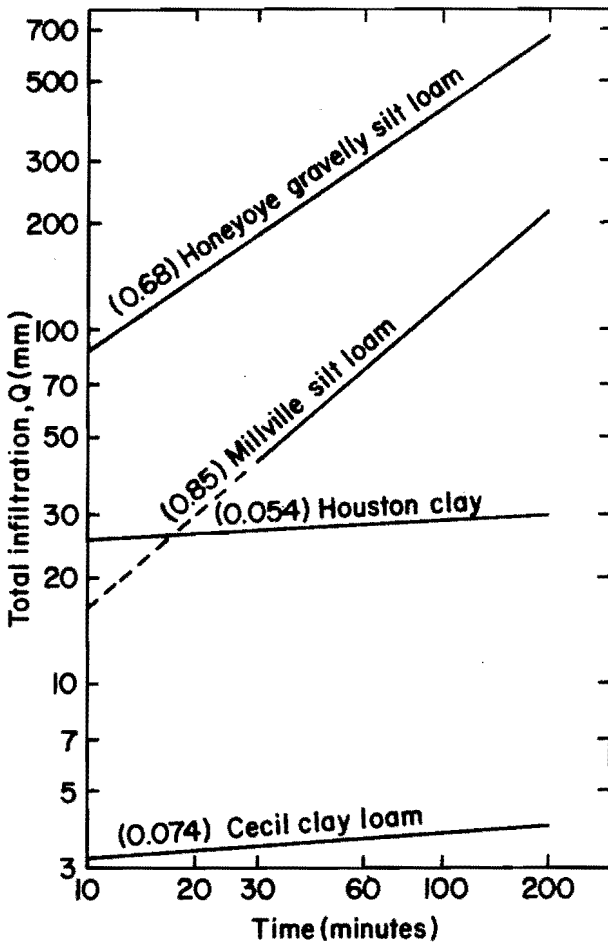


Figure 3. Infiltration of water into various kinds of soil in the field. Steep slopes (large values of a shown in each curve) indicate stable soil structure; those with small values of a deteriorate and swell when water wets them (after Taylor 1961).

When data are plotted as rate versus time in linear scale (Figure 4), the difference in infiltration rates between the soils is much more apparent. These curves tend to illustrate the extremes found in nature. It is difficult to visualize rainfall intensity greater than the infiltration rate of Honeyoye gravelly silt loam. On the other hand, even a moderate rain would likely exceed the rate of water movement into Cecil clay loam or Houston clay after 20 or 30 minutes.

Attempts to model infiltration mathematically continue. Morel-Seytoux and Khanji (1974) insist that equations of infiltration are now available that are both simple and accurate, and of practical value to the hydrologist.

**Measurement of Infiltration**

Infiltration rates measured on disturbed samples in the laboratory are not representative of field conditions. Ring infiltrometers have been used in the field to measure infiltration capacity, but these too have limitations. At best, the ring infiltrometer may be used as an index of infiltration capacity to compare rates between sites. Likewise, flooding field plots is a poor duplication of the natural processes unless the soils being tested flood naturally.

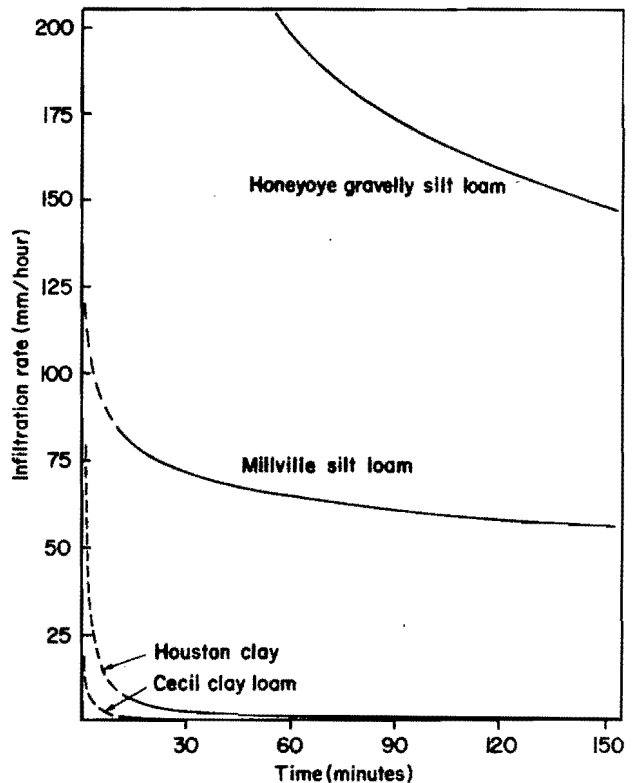


Figure 4. Data from Figure 3 converted to infiltration rate and plotted in linear scale. The dashed portions of the curves between 1 and 10 minutes are extrapolated.

Rainfall simulators (sprinkler-type infiltrometers) have been widely used in the western United States since the 1930's (Beutner et al., 1940; Dortignac, 1951). Designs vary in attempts to duplicate natural rainfall and meet specific needs (Blackburn et al., 1974). Rainfall simulators are doubtless the best method available for field evaluations of infiltration. However, results are not necessarily the same as might occur under natural rainfall of varying intensity and intermittency, and, as with all small plot studies, interpretation and extrapolation of results to large areas are difficult.

Attempts have been made to estimate infiltration on watersheds from rainfall and runoff data and from hydrograph analysis. If all runoff from a storm is overland flow, this method will generally give quantitative results. However, the infiltration rate derived is an average rate for the watershed; it is not representative of a specific area or areas on the watershed, where most overland flow is likely to be generated. Infiltration varies greatly among soil types, slope position, distance from channel, and other factors, and the effects are completely integrated in a single streamgage measurement, although the runoff observed may originate within a relatively small portion of the watershed.

The situation is much more complicated and estimates of infiltration by this method are meaningless when storm runoff includes both overland and subsurface flow. While arid range lands may produce little or no subsurface flow, particularly during short, intense storms, the opposite holds for humid forest lands. Since hydrograph separation of surface and subsurface components is usually not possible, the method has little practical value on most forest lands, and is of questionable value on ranges.

#### **Effects of Grazing and Other Land-Use Practices on Infiltration**

Of particular interest to the land manager are the effects of land use on infiltration rate. The pores in the soil medium act as a "plumbing system." This system can be damaged or interrupted by compaction, mechanical disturbance, reduction of protective cover, fire, and other forms of disturbance associated with land-use activities. The more important factors affecting the infiltration rate, which in turn are directly influenced by land use, are underlined in Figure 1. The beneficial influence of plant cover on infiltration is well known. However, the relation shown in Figure 2 may not be entirely caused by the amount of vegetation—the low infiltration rate on the sparsely covered soils may be influenced by factors other than cover.

The influence of grazing on infiltration has been the subject of considerable study. Recent reviews include those by Branson et al. (1972), Heady (1975), and Stoddart et al. (1975). Grazing animals remove plant material, and

disturb and compact the soil surface to the detriment of infiltration. The magnitude of the effect is influenced not only by the intensity of grazing, but by the type of soil and vegetation, climate, topography, and by class, age, and management of livestock. While light to moderate grazing usually does not produce intolerable reduction in infiltration, there is ample evidence that heavy, indiscriminate grazing seriously affects the capacity of soil to absorb water.

#### **Soil Wettability and Effect of Fire on Infiltration**

Nonwettability or water repellency has become recognized in recent years as the major cause of poor infiltration in certain range and forest soils, particularly burned chaparral lands (Krammes and DeBano, 1965). Water repellency is indicated when drops of water placed on the soil surface form beads that do not penetrate for at least 5 seconds (DeBano, 1969a). While not always of problem proportions, naturally water-repellent soils have been found under many forest and range vegetation types (DeBano, 1969b; Foggin and DeBano, 1971; Meeuwig, 1971; Scholl, 1971; Zwolinski, 1971). The repellency is caused by organic materials, mainly aliphatic hydrocarbons (Savage et al., 1972), which cover soil particles. Coarse sandy soils are more susceptible than fine soils (Jamison, 1969), since the smaller surface area of the coarse particles is more easily coated.

Forest fires can induce extreme repellency (Figure 5) by concentrating and increasing persistence of the naturally water-repellent materials in a layer just below the ash and mineral surface (DeBano et al., 1970). The water-repellent layer apparently forms when volatile organic matter diffuses downward from the burning litter and condenses onto soil particles a few centimeters deep, depending on the intensity of the fire. Because of the steep thermal gradient that develops in the mineral soil, temperatures as high as 1000°C above the surface may reduce to only 200°C to 300°C a few centimeters below the surface. Scholl (1975) found that the volatilized material was almost completely lost above 270°C; the soil becomes wettable again at higher temperatures. Below 270°C, sufficient material is trapped and condensed to produce water repellence.

Erosion and flooding are particular hazards associated with water repellency induced by fires. The most vulnerable period is the first year after fire; thereafter the infiltration rate of the soil gradually recovers.

What can be done to speed the recovery process? The problems encountered here are by no means solved. Rice (1973) suggests that only direct physical or chemical attack on the water-repellent layer is likely to be a practical means of reducing erosion during the first year. Wetting agents have been applied experimentally with varying success (DeBano et al., 1967; Rice and Osborn, 1970;

DeBano and Conrad, 1974). It appears that more research is needed to find quick, efficient methods of restoring infiltration properties to burned areas that have become high flood and erosion hazards.

**Percolation Process**

The basic process of rainwater percolating through the zone of aeration is depicted in Figure 6. A deep homogeneous soil profile is indicated, with the water table well below the root zone. Annual precipitation exceeds evapotranspiration, so that the soil (regolith) below the root zone never dries. As rain (or snowmelt) enters the soil it first satisfies any water deficits created by evapotranspiration. As long as water moves as a wetting front (curves 1 and 2) into dry or relatively dry soil, capillary forces predominate. When water content reaches "field capacity," the energy gradient produced by capillary forces has weakened and gravity remains as the dominant downward driving force. When rain stops, water in excess of field capacity quickly drains from the upper soil, and the water content profile takes the configuration depicted by curve 3. As rainless days continue, evapotranspiration depletes soil water (curve 4) in the root zone, and the cycle repeats.

The large cyclic fluctuations in water content near the surface and in the root zone diminish as the water moves down through the zone of aeration. This intermediate zone never depletes below field capacity, so a relatively small increase in water content is sufficient for resumption of downward flow. Flow will continue in this zone long after the moisture content in the root zone drops below field capacity.

Some discussion of the "field capacity" concept is appropriate at this point. Although the concept is vague and lacks precise definition, it is useful in describing soil-water conditions in which the energy potentials for moving water downward are almost in equilibrium with opposing forces. Actually, water continues to drain from soil long after the arbitrary 1- to 3-day cutoff point established for agronomic purposes. A freely draining soil mass a few feet thick situated beneath the root zone may continue to yield

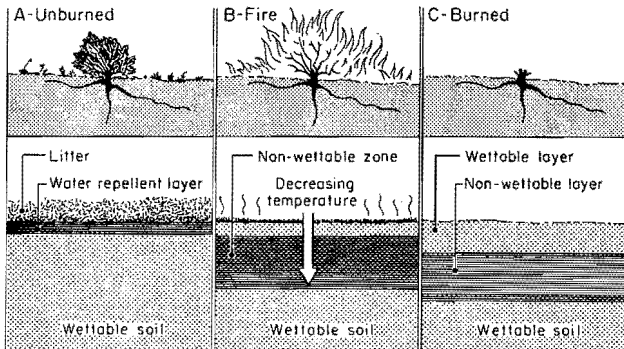


Figure 5. Schematic of effects of fire on water repellency in chaparral (after DeBano et al., 1967).

water for months without rain (Hewlett, 1961; Hewlett and Hibbert, 1963; Scholl and Hibbert, 1973).

An important aspect of percolation is its rate. The movement of water can be expressed as velocity of flow, or generally most useful, volume rate or flux. The Darcy equation, first developed almost 120 years ago for saturated flow through sand, was modified more than 40 years ago for unsaturated flow as well. This modification requires that the transmission coefficient known as the hydraulic conductivity and at least one of the forces acting on the water be dependent on the degree of saturation (Nielson and Corey, 1974). The equation for steady-state unsaturated vertical flow, Q, is:

$$Q = -K(\theta) \frac{dH}{dz} \dots\dots\dots(2)$$

where K(θ) is the unsaturated hydraulic conductivity, which is dependent on water content, θ, and dH/dz is equivalent to the net force acting on the water. The hydraulic head, H, is the sum of the gravitational head, z,

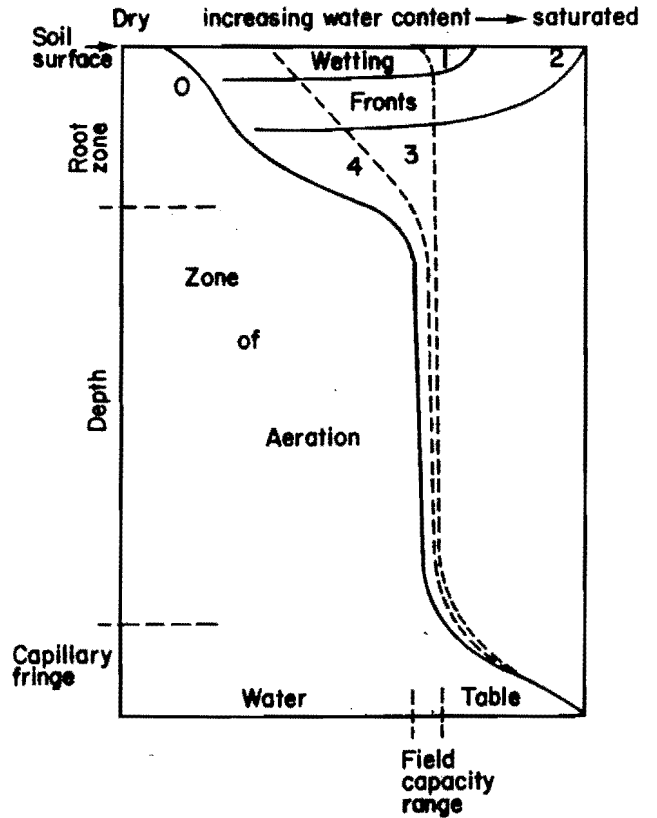


Figure 6. Idealized distribution of soil water in a deep homogeneous soil profile. (0) Rain begins after dry period, (1) after some minutes of rain intensity less than infiltration rate, (2) after some hours of rain intensity equal to or greater than infiltration rate, (3) after few days without rain, (4) after many days without rain.

and the matric potential (capillary potential) head  $h$ , also a function of the soil water content.

The hydraulic conductivity decreases greatly as soil drains and dries. Rate of flux (volume of water moving through the soil measured as depth per unit area) may range from the order of tens or even thousands of millimeters per day when soil is at or near saturation to the realm of one thousandth millimeter per day as the soil dries to the point where plants can no longer extract water. This rate also varies with soil texture, as would be expected considering size of pores and the tenacity with which various size fractions "hold" water. A coarse soil will transmit water much faster at high water content than will a fine soil, although at low water content this is not always true.

### Measurement of Soil Water Movement

Developing methods for measuring soil water movement accurately and efficiently has occupied the attention of scientists and engineers for many years. Although most of the technology has been developed for agriculture, it applies to range and forest situations as well. The wildland manager may be little interested in irrigation and drainage problems, but he is concerned with water production, recharge of aquifers, and efficient utilization of available water. Often his interest goes deeper into the soil and regolith than that of his agricultural counterpart.

Taylor et al. (1961) cite two general objectives for measuring soil water: One is to determine the moisture content of the soil, and the other is to determine the amount of work that must be done to remove water from the soil. Stressing the measurement of water movement in the zone of aeration, Nielson and Corey (1974) discussed how these concepts of water content and energy relations are used to determine water movement, and added a third approach which utilizes tracers to identify the direction and rate of flow. Their purpose was to present the state-of-the-art of these approaches. Since that is also the purpose of this paper, I will briefly summarize their review.

#### 1. Changes in soil water content

The first approach to measuring water movement is based on the conservation of the mass of water, or the change in the distribution of soil water with time. The rate of water movement at a given soil depth is calculated by integrating the time rate of water content change from the soil surface to that depth, discounting evapotranspiration. The success of this method hinges on reliable evaluation of evapotranspiration during rainless periods (a difficult accomplishment on forest and range lands), and the accurate measurement of volumetric water content as a function of time and soil depth.

The most simple and direct method of measuring water content is gravimetric analysis. Drawbacks are that it is time-consuming and requires repetitive removal of soil samples, destroys the sample site, is limited to a few meters depth at best, and yields accurate values only when the volume of the sample in the field is known. Improvements are continually being made, as exemplified by use of microwave ovens in which a drying time equivalent to 105°C for two days in conventional ovens is reduced to about 30 minutes (Miller et al., 1974). Despite these innovations, it is doubtful that gravimetric sampling can compete with nuclear methods inasmuch as they are rapid, give repetitive measurements in the same bore hole, and can be made to great depths. Also, fully automatic meters are now available. A disadvantage is installing access tubes in rocky soil. Other methods for measuring water content are continually being developed or improved, such as utilizing the relationship between the amount of soil water present and thermal conductivity of the soil.

In spite of these advances, estimates of water flow rate by measuring changes in water content are generally poor unless seasonal averages are sought, or rates of flow are relatively large. In these cases, changes in water content become less important, reducing this technique to a budget of water entering (infiltration) and leaving (evapotranspiration) the soil surface. The excess is the water that eventually reaches groundwater.

#### 2. Forces and transmissibility

The second approach consists of calculating water movement from measured values of the forces acting on the water and the soil transmissibility coefficients. This technique requires accurate measures of hydraulic conductivity and matric potential as a function of soil depth for a particular time. Values of the matric potential head,  $h$ , are obtained readily with tensiometers. A summary of the applicability of this technique using Equation 2 has been given by Nielsen et al. (1972a), as well as by others who have written textbooks and monographs treating methods for obtaining the hydraulic conductivity (Black, 1965; Baver et al., 1972; Kirkham and Powers, 1972; Taylor, 1972; Hillel, 1971; Nielsen et al., 1972b). Referring to the use of this approach, Nielsen and Corey (1974) state that "although methods for measuring  $K(\theta)$  are available, relatively few scientists and engineers have taken opportunity to use them." They further state that several investigators have ascertained the flow of water in the zone of aeration to a relatively high degree of accuracy by combining approaches 1 and 2. Specifically, they solve soil water flow equations for transient conditions using both tensiometric and nuclear techniques, with the resulting measurements recorded and analyzed automatically.

### 3. Movement of tracers

Measurement of both direction and rate of water flow through the soil is possible with tracers. However, Nielsen and Corey (1974) warn that the use of tracers to identify the rate of water transport through unsaturated soils—as opposed to saturated conditions—requires a thorough analysis of the potential interaction of the tracer with the soil particle surfaces that are normally negatively charged and whose effects become more pronounced as the soil water content decreases. Recent works by Kirda et al. (1973, 1974) examine these interactions. These and other studies suggest that, while tracers can be used to evaluate water movement in the zone of aeration, their use has not been fully developed or proved under field conditions.

In summary, Nielsen and Corey (1974) refer to an unresolved problem, the difficulty of extrapolating measurements and results from point sources or small plots to field situations. This becomes particularly difficult when the heterogeneity of forest and range soils and topography are considered. Thus, utmost care must be taken to ascertain the accuracy, precision, and applicability of direct measurements of soil water in the zone of aeration to field conditions; otherwise, results will be specific as to their location, and their extrapolation to large areas will be conjectural.

### Groundwater

Groundwater is defined by Butler (1957) as “the general subsurface water body in the zone of saturation.” Most scientists and engineers visualize substantial aquifers, usually regional in extent, with the upper boundary being a defined water table. These systems are a major source of usable water in many parts of the world; many are yet undeveloped. Forested areas in particular, and range lands to a lesser extent, produce good quality recharge to groundwater. Arid lands produce relatively little recharge, but the amount they do produce is often concentrated in alluvium along stream courses where it can be easily recovered.

Because of the commercial importance of groundwater, its science is relatively advanced, except for certain neglected areas. Many papers and texts are available on scientific principles and engineering aspects of groundwater. One text in particular (Gray, 1973), which contains a section on groundwater hydrology by James M. Murray, has more than general application to range lands because the data used are primarily for prairie conditions in Canada.

Rather than attempt further discussion of the general groundwater subject, I would like to direct the remainder of my remarks to the poorly understood and somewhat

controversial function of local subsurface water systems in the generation of streamflow in steep, headwater catchments.

### SUBSURFACE GENERATION OF STREAMFLOW

Forty years ago, Horton (1935) concluded that streamflow consisted of “two chief components, direct surface runoff and ground water flow.” His work with infiltration led him to believe that stormflows and floods were caused by the failure of rain to enter the soil, and that streamflow during dry periods was fed by groundwater aquifers. The fact that lack of infiltration produces overland flow and floods is not to be denied, to which anyone can attest who has been caught in the desert or in an open field during a summer downpour. In fact, this is the very type of experience that makes it easy for the layman to believe that surface runoff is the only source of floods.

The Hortonian concept prevailed for many years, and it is still valid so far as it is properly applied to land surfaces that do not accept water readily. Much of the western range lands are in this category. By the 1940's, however, forest hydrologists in the eastern United States were becoming increasingly aware that overland flow was not being generated on forested slopes in sufficient quantity to account for stormflows being measured in first-order streams. Hoover and Hursh (1943) and Hursh and Brater (1941) determined the need to account for subsurface flow in storm hydrographs from small mountain watersheds in the southern Appalachians. Horton himself (1943) recognized that some soils were capable of absorbing all the water that fell on them. With reference to the Little Tallahatchie drainage basin in Mississippi, he observed that “owing to somewhat unusual conditions, surface runoff rarely occurs from soil well protected by forest cover.”

The need to account for and explain the subsurface component of stormflow led to use of the terms “interflow” and “quick return flow,” which have never been clearly defined. Much uncertainty exists about flow paths and how water actually moves downslope through the soil fast enough to contribute significantly (Freeze, 1972) to stormflow. Some hydrologists believe that water moves rapidly downslope through old root channels and animal burrows (Whipkey, 1967; Aubertin, 1971), while others claim that the channel system expands during storms, in effect increasing the contact area between channel and slope and at the same time decreasing the distance that water must move downslope through the soil to become channelized flow (Hewlett and Nutter, 1970).

There is an increasing awareness today that subsurface flow, however short the travel distance through the soil, plays an important role in the hydrology of small watersheds. Rainwater may infiltrate and travel for some distance through the soil, then resurface to continue overland to the stream, or the reverse may occur when



rain fails to infiltrate in one area but does lower on the slope where infiltration is greater. Not only is timing of water delivery affected by subsurface paths, but water quality as well. Subsurface flows are only briefly exposed to surface contaminants, but in mixing with the soil solution they may differ chemically from surface water.

The mechanism of stormflow generation from rainfall on upstream areas may be viewed as occurring in one of three ways:

1. The classical Hortonian concept, where overland flow is generated by rain intensity exceeding infiltration capacity uniformly over the area or on portions of the watershed.

2. Overland flow is generated on areas close to streams that become saturated when local water tables rise to the surface, primarily as a result of rapid infiltration of rainwater filling the soil. Direct subsurface flow contributes little to stormflow.

3. Subsurface flow is generated by rapid infiltration of rain, and moves laterally beneath the surface into streams which expand and lengthen as rainfall progresses. Direct overland flow contributes little to stormflow.

The first mechanism is no longer considered a viable process on most forested lands and on many other lands where soils are permeable and capable of accepting all but the most intense rain. (The rare event of great intensity is outside the scope of this discussion.) The most damaging evidence against this type of flow is that (1) infiltration is seldom limiting, (2) there is a lack of physical evidence for a significant amount of overland flow of this type, and (3) the delay in response of outflow to rainfall in the first-order basin suggests subsurface rather than surface generation of most storm discharge (Hewlett and Nutter, 1970).

Where infiltration is limiting and overland flow is the dominant source of stormflow, the "partial area" or "source area" concept of streamflow generation is recognized as a means to better model the runoff process (Betson and Marius, 1969; Engman and Rogowski, 1974). The idea that certain areas are critical in stormflow generation applies whether the runoff is surface or subsurface. Recent debate has focused on application of the concept, and whether the source areas are fixed or variable (Hewlett, 1974).

The second mechanism of stormflow generation appears viable for certain areas, as demonstrated by Dunne and Black (1970 a,b) on a small Vermont watershed. They stress that the importance of an area as a source of storm runoff depends on its ability to produce overland flow, not subsurface flow, although some of the latter was detected. They further stated that the partial areas contributing quick runoff could expand or contract seasonally or during a storm.

The third mechanism, subsurface generation of stormflows on lands where infiltration is not limiting, has its strongest proponents among forest hydrologists in the eastern United States (Hewlett and Hibbert, 1967; Pierce, 1967; Whipkey, 1967; Hewlett and Helvey, 1970; Hewlett and Nutter, 1970; Troendle and Homeyer, 1971; Lull and Reinhart, 1972; Nutter, 1973; Hornbeck 1973). Opponents maintain that water moves too slowly through the soil—that only immediate channel-side areas could contribute significantly during the stormflow period. Freeze (1972) showed in a theoretical study that the conditions necessary to support subsurface stormflow were quite stringent. Dunne and Black (1970a) argued that subsurface flow was too slow (calculated at 100 to 500 times slower than overland flow) to contribute significantly to stormflow.

These problems are recognized and dealt with in a working hypothesis of subsurface stormflow generation proposed by Hewlett and Nutter in 1970, and more recently reemphasized and defended by Hewlett (1974). Known as the "variable source area" concept, emphasis is on the dynamic nature of the contributing areas. The source areas will vary from basin to basin, but in the simple case of a permeable basin with a dendritic drainage network, the source area may expand during rainfall as shown in Figure 7. Depending on the storage capacity of the basin slopes, the area actually involved in producing stormflow may vary from less than 1 percent of the basin during small storms (essentially channel precipitation) to perhaps 50 percent or more in very large storms. Stormflow and its source area increase at the beginning and decrease at the end of rainfall as a result of two simultaneous processes: slope water movement and channel expansion and shrinkage.

#### *Slope water movement*

Rain in the channel causes the first rise in the hydrograph. As rain continues, channel precipitation is augmented within a few minutes by expansion of the surface and subsurface areas that contribute water by (1) displacement of water stored in the channel banks and seep areas, (2) direct flow of new rainwater through the large pores of the expanding channel banks, and (3) any overland flow that may develop from impervious rock, road, or soil surfaces adjacent to the stream. The solid black arrows within the soil mantle in Figure 8 represent the relative effect of a large rainstorm on direct runoff as the distance upslope increases. Note that rainfall near the ridgetop contributes little or nothing to stormflow, although percolation within the soil mantle (blown-up soil sections) begins to displace stored water downslope. This constant downslope migration of water during nonstorm periods keeps the lower slopes and channel-side areas much wetter than upper slopes.

*Channel expansion*

As rainfall continues to soak the slopes, the capacity of the soil mantle near the stream to transmit water is exceeded, and the water emerges at the surface farther upslope or upstream. The merging water quickly collects in draws to form intermittent channels, thus extending the effective length and width of the channel system many fold.

*Baseflow*

When rainfall ceases the entire process reverses, stormflow subsides, and the intermittent or temporary channel system shrinks back to its normal configuration. Water is still moving downslope through the zone of aeration (Figure 8), however, and this water continues to feed the stream for a long time. Although the drainage of unsaturated soil is relatively slow, and gradually becomes still slower, a layer of unsaturated soil a few feet thick below the immediate reach of evapotranspiration will yield

water for months without further recharge at rates believed sufficient to maintain streamflow in small headwater catchments (Hewlett, 1961; Hewlett and Hibbert, 1963).

On gentle terrain with extensive groundwater aquifers close to the surface, baseflow is more likely to be generated by groundwater feeding effluent streams. However, in steep terrain, typical of so much wildlands, it is difficult to visualize extensive groundwater systems conforming with the topography in a manner that would produce effluent seepage along stream courses sloping, for example, at 20 percent. Thus baseflow, like stormflow, can have a variable source area of saturated-unsaturated complexity not always conforming to traditional concepts of groundwater hydrology, but nevertheless operating according to basic laws of water movement in porous media.

A recent study by Stephenson and Freeze (1974) on Reynolds Creek Experimental Watershed in southwest

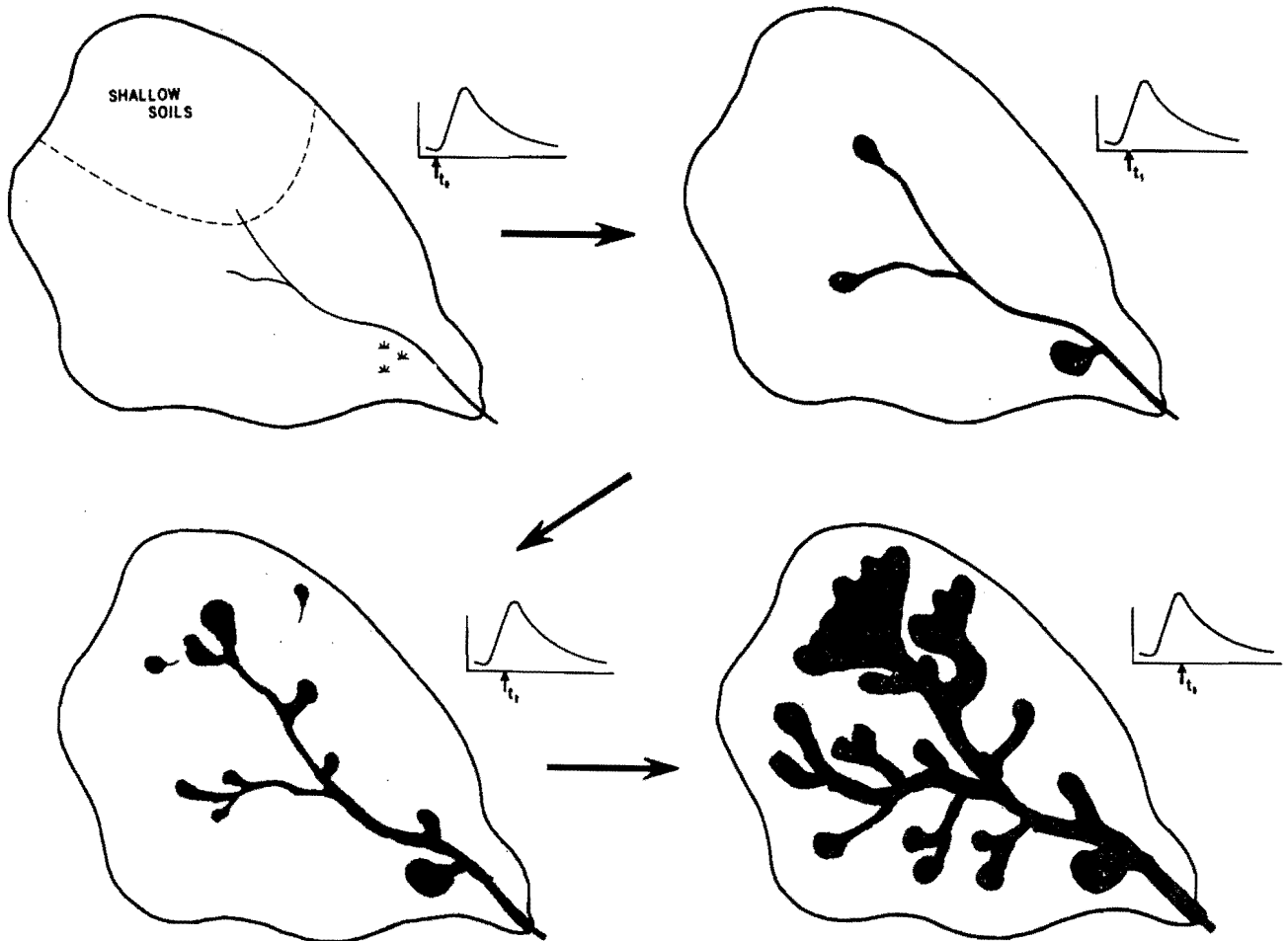


Figure 7. Diagram of expanding source area during a large rainstorm. Arrows along the time line of the hydrograph show relative discharge associated with the source area, which may expand to one-third or more of the basin at peak flow (after Hewlett and Nutter 1970).

Idaho illustrates the complexity of subsurface movement of water on steep slopes. They applied a mathematical model of subsurface flow to snowmelt runoff on a hillside segment of a gaged catchment. Although they could not account for some inconsistencies between the model and measured outflow, they concluded that "transient saturated-unsaturated subsurface flow can deliver snowmelt infiltration through high-permeability low-porosity formations fast enough to be the sole generating mechanism of runoff from an upstream source area."

In drier climates, recharge may seldom, if ever, occur over most of the basin. Recharge sufficient to produce baseflow may be restricted to depressions and alluvium along channels where overland flow concentrates and soaks in. Unless fed by extensive groundwater aquifers, baseflow decreases rapidly in semiarid lands because the source areas are often limited to intermittent channel systems.

A lot has been left out of this oversimplified presentation of streamflow generation. A lot remains to be learned. Some of these concepts will, undoubtedly, undergo modification, but from it all should emerge a

physically based working model that will realistically account for generation of streamflow in headwater basins.

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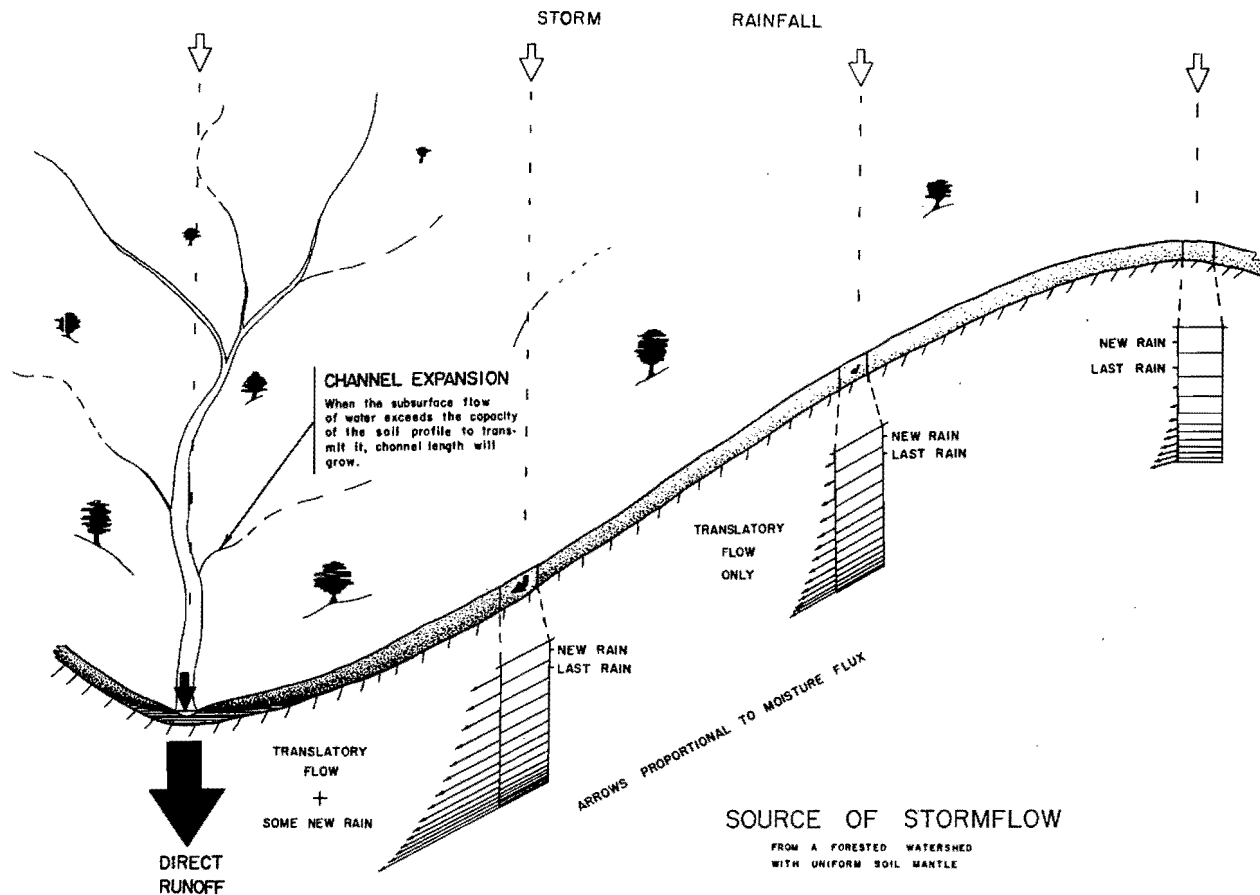


Figure 8. An idealized section through a forested upland watershed, drawn to illustrate the variable source area responsible for direct runoff and baseflow (after Hewlett and Hibbert 1967).

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# Soil Water Movement: Infiltration, Redistribution, and Groundwater Movement

T. Talsma\*

## INTRODUCTION

Knowledge of the physics of soil water movement is crucial to the solution of problems in watershed hydrology; for example, the prediction of runoff and infiltration following precipitation, the subsequent distribution of infiltrated water by drainage and evaporation, and the estimation of the contribution of various parts of a watershed to the groundwater store.

Both surface runoff and lateral movement of groundwater contribute to open streamflow. Runoff is the subject of another paper in this series and lateral flow of groundwater will be briefly reviewed only. In the Australian context many of the rivers in rangelands are influent streams that supply rather than deplete groundwater in the major aquifers. The main subjects of review will therefore center on factors important in understanding infiltration behavior and the distribution of infiltrated water from the initially wetted soil layers.

It is usually considered that rainfall or artificially applied water, either for irrigation or groundwater recharge, covers a sufficiently large area to enable the process to be treated as one-dimensional unsaturated vertical flow to the deepest layers to be considered. The possibility of significant lateral sub-surface flow (interflow) is recognized, but this subject is controversial and will not be treated here.

In both soil physics and hydrology, water transport problems in non-swelling soils are usually solved using the basic equation

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left( K \frac{\partial \Psi}{\partial z} \right) - \frac{\partial K}{\partial z} \dots \dots \dots (1)$$

where  $\theta$  is volumetric water content,  $K$  is hydraulic conductivity,  $\Psi$  is soil water potential,  $z$  is the vertical coordinate, measured positive downwards, and  $t$  is time.

Both  $K$  and  $\Psi$  are nonlinear functions of  $\theta$ , usually strongly so.  $\Psi(\theta)$  is hysteretic, but  $K(\theta)$  appears in general not to be.

During infiltration into a homogeneous soil at uniform initial moisture content, flow is non-hysteretic, and by introducing the soil water diffusivity  $D(\theta) = K(\theta) \partial \Psi / \partial \theta$ , Equation (1) may be rewritten:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left( D \frac{\partial \theta}{\partial z} \right) - \frac{\partial K}{\partial z} \dots \dots \dots (2)$$

A similar expression has been derived (Philip, 1969c) to describe infiltration into saturated swelling materials:

$$\frac{\partial \vartheta}{\partial t} = \frac{\partial}{\partial m} \left[ D \frac{\partial \vartheta}{\partial m} \right] - \frac{\partial}{\partial m} [(1 - \gamma)K] \dots \dots \dots (3)$$

The moisture content is now expressed as the moisture ratio,  $\vartheta$ ,  $m$  is a material coordinate, and  $\gamma$  is the wet specific gravity.

It is not my purpose to discuss solutions of Equations 1-3 in detail, since this has been done elsewhere. For example, Fleming and Smiles (1975) reviewed the soil physical and hydrological bases of infiltration in the context of catchment hydrology. Rather we seek to confirm the predicted differences in infiltration behavior between swelling and non-swelling soils by examining results of recently completed field studies. Further, it is useful to discuss and compare measurements of physically based infiltration parameters and to indicate their possible value to watershed hydrology. Redistribution problems will be treated by considering some numerical solutions of Equation 1, while deep drainage to groundwater is further treated by using a water balance model.

## INFILTRATION

### Comparison Between Rigid and Swelling Soils

Accurate prediction of cumulative infiltration,  $i$ , infiltration rate,  $v$ , and soil moisture content,  $\theta$ , as a

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function of time,  $t$ , and distance,  $z$ , below the soil surface is possible in a rigid uniform soil at uniform initial moisture content when it is subjected to a step-function change of moisture content,  $\theta$ , e.g. by ponding, at the soil surface. For example, the solution of Equation 2 for cumulative infiltration,  $i$ , in this case is

$$i = St^{1/2} + At + Bt^{3/2} + \dots \quad (4)$$

where  $S$  is sorptivity, and  $A$  and  $B$  are coefficients in the full analysis of Philip (1957a). For swelling soils, Equation 3 can similarly be solved to yield an expression equivalent to Equation 4 for cumulative infiltration. The details are elaborate (Philip, 1969c).

Comparison of Equations 2 and 3, however, shows that, in swelling soils, the influence of the gravitational term should be less, as it is reduced by the inclusion of the term  $(1-\gamma)$ . This has been demonstrated by Smiles (1974) in laboratory experiments on two-phase (solid-liquid) flow. Moreover, in mineral soils  $\gamma > 1$ , so that infiltration in swelling soils may show similarity to capillary rise in rigid soils and, conversely, capillary rise may be similar to infiltration in a rigid soil (Philip, 1972). Smiles and Colombera (1975) show, for infiltration, that this is the case where there is a net increase in gravitational potential energy of the soil system.

We now examine the dynamics of water movement in field soils. Two of these, Yandera loam and Banna loamy sand

sand, may be considered as non-swelling materials, while the others, Willbriggie clay (B-horizon) and two black soils derived from basalt (located at Ginninderra Creek and Cooma Creek), exhibit swelling and shrinking. The  $K(\theta)$  and  $D(\theta)$  relations of the loam and loamy sand, derived from *in situ* measurements, are given in Figure 1, and the calculated values of  $S$ ,  $A$ , and  $B$  (Equation 4) for these materials, together with the hydraulic conductivity at saturation ( $K_1$ ), in Table 1. Figure 2 shows, for four soils, the cumulative capillary rise,  $i_c$ , as a function of  $t^{1/2}$ . In this case,  $i_c = St^{1/2} + At + Bt^{3/2} + \dots$  (Philip, 1969a), where the meaning of the symbols is exactly as in Equation 4. The  $t^{1/2}$ -scale is preferred over a  $t$ -scale, since results plotted in this manner indicate clearly when the gravitational terms in Equations 2, 3, and 4 contribute significantly to either cumulative infiltration or capillary rise.

The data presented in Figure 2 permit the following conclusions: (a) The prediction that in swelling soils the dynamics of capillary rise may be similar to that of infiltration is adequately supported, under the experimental conditions; (b) Deviation from  $t^{1/2}$  behavior occurs much later in swelling soils than in rigid materials, the approximate times being 3 min. for Yandera loam, 16 min. for Banna loamy sand,  $4 \times 10^3$  min. for black clay, and  $10^4$  min. for Willbriggie clay.

The above comparison of capillary rise behavior is deliberate since field infiltration experiments, using ponded water on the surface of swelling clay soils, are

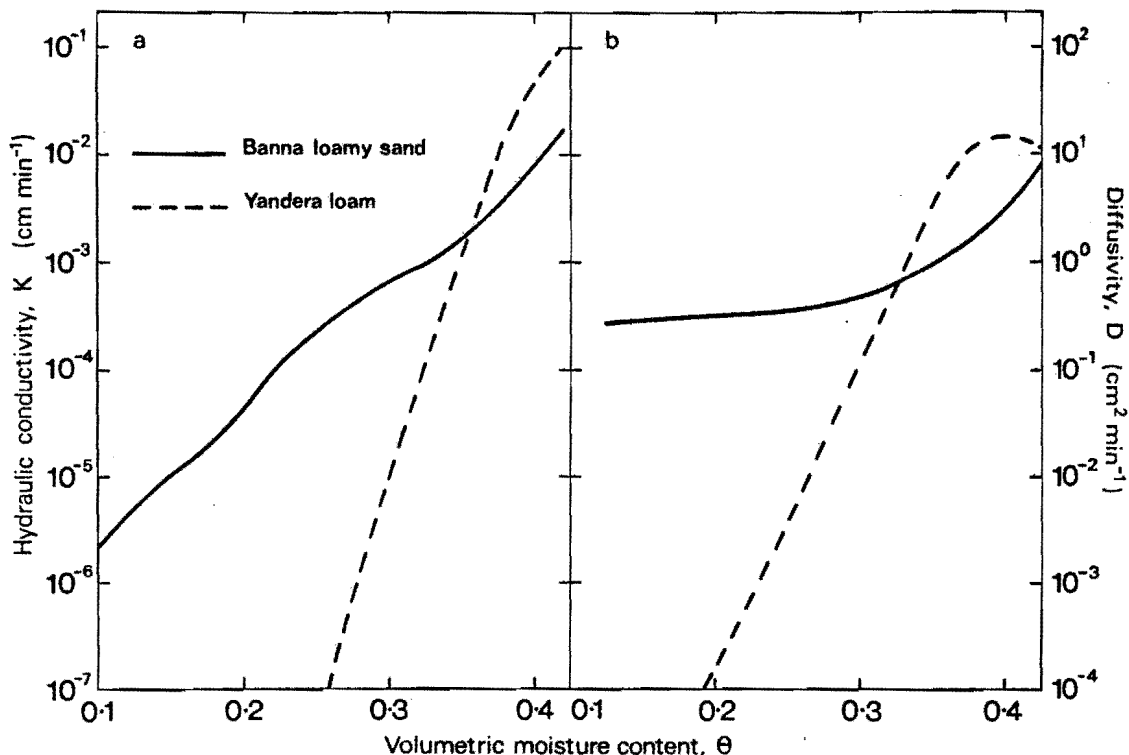


Figure 1. Hydraulic conductivity and diffusivity relations for Banna loamy sand and Yandera loam.

generally more difficult to interpret in terms of swelling soil theory. The difficulty is associated with the presence of wide surface cracks when the soil is relatively dry. Some cracks persist at relatively high moisture contents. Initially, water penetrates rapidly, to fill up cracks, from where it is absorbed into the bulk of the soil. An example of this type of behavior is shown in Figure 3, for Cooma Creek black clay at various initial moisture contents. The initial rapid intake increases with decreasing soil moisture. In all three experiments the subsequent infiltration proceeds linearly with  $t^{1/2}$  to the limit of experimental time (170 min.).

Failure to measure final, steady infiltration rates in clay soils has often been noted. Such rates are usually an essential part of an infiltration function used in watershed modeling, and they are normally measured during experiments of a few hours duration when the soil is

initially at "field capacity." In rigid soils, final infiltration rates under these conditions are soon achieved (Philip, 1957b). We note, for example, that the final infiltration rate, equal to the saturated hydraulic conductivity, in relatively dry Yandera loam (Table 2) is achieved at 300 min. In the swelling soils (Figures 2 and 3), however, infiltration is proportional to  $t^{1/2}$  for very long periods; thus, failure to rapidly achieve a steady rate, proportional to  $t$ , is entirely as expected.

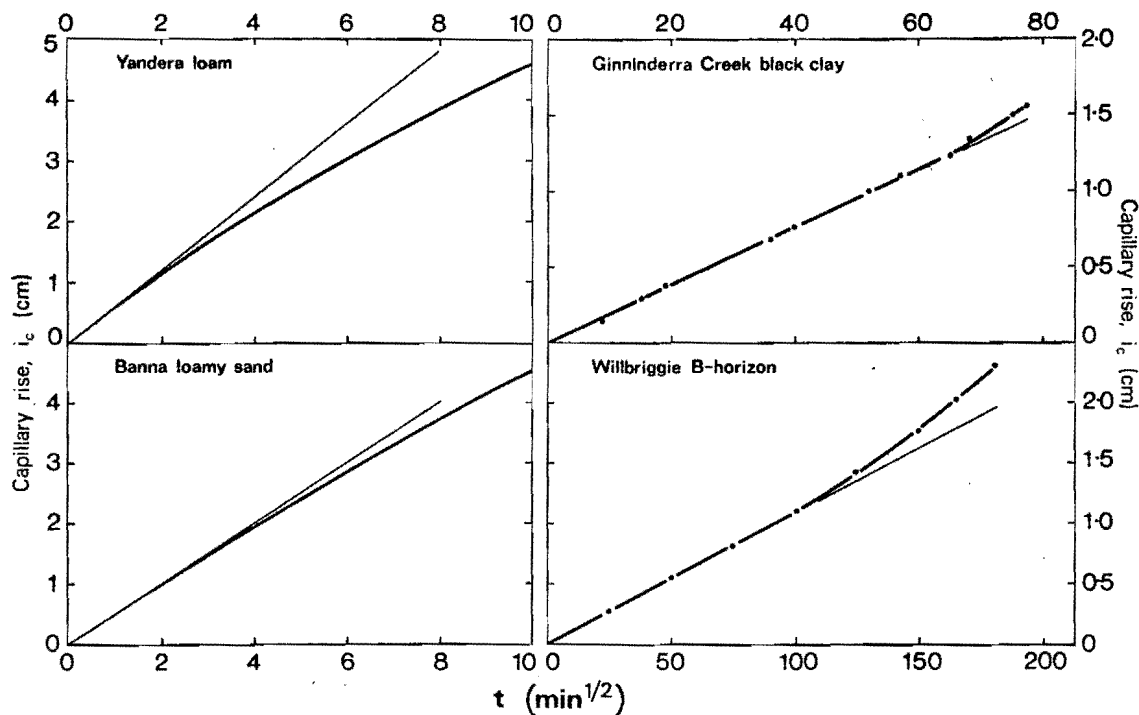
**Heterogeneous Soils, and Other Boundary Conditions**

The comparison of infiltration between rigid and swelling soils has been for uniform materials, subjected to a simple set of boundary conditions by assuming instantaneous ponding at the surface. The theory in this case has been thoroughly explored. This has permitted the

**Table 1. Infiltration characteristics for Yandera loam and Banna loamy sand.**

Soil Type	$\theta_0$	$\theta_1$	S ( $\text{cm min}^{-1/2}$ )	A ( $\text{cm min}^{-1}$ ) $\times 10^{-2}$	B ( $\text{cm min}^{-3/2}$ ) $\times 10^{-4}$	$K_1$ ( $\text{cm min}^{-1}$ ) $\times 10^{-2}$	$v^a$ ( $\text{cm min}^{-1}$ ) $\times 10^{-2}$
Yandera	0.18	0.42	0.60	1.99	5.83	5.20	5.24
Banna	0.07	0.43	0.51	0.63	0.79	1.80	2.30

<sup>a</sup>Infiltration rate  $v$  at  $t = 300$  min.



**Figure 2. Capillary rise in non-swelling (Yandera loam and Banna loamy sand) and swelling soils. Thinner lines are gravity-free solutions.**



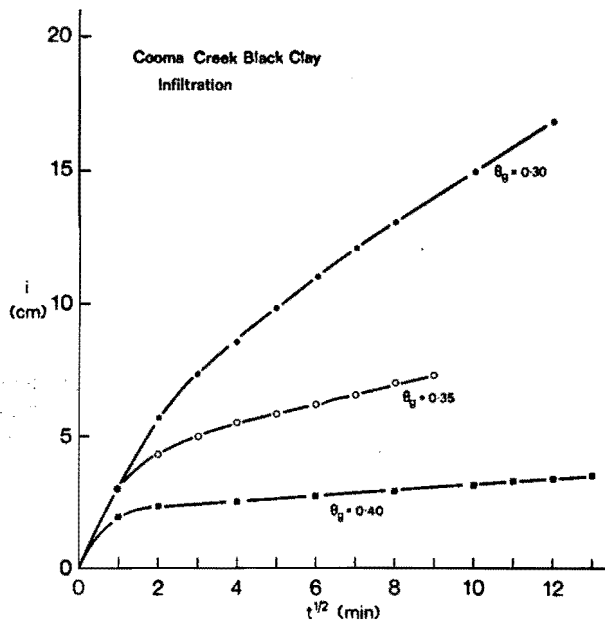


Figure 3. Infiltration at different initial moisture contents in a swelling soil.

Table 2. Variation of sorptivity,  $S$  ( $\text{cm min}^{-1/2}$ ), with imposed moisture content,  $\theta_1$ , and moisture potential,  $\Psi$  (cm), for Pialligo sand at initial moisture content  $\theta_0 = 0.01$ .

$\Psi$	0	-5	-10	-15	-20
$\theta_1$	0.34	0.30	0.25	0.19	0.15
$S$	1.46	1.10	0.81	0.31	0.10

exposition of important differences between these materials. However, neither soil uniformity nor the simple boundary condition are usually appropriate to watershed hydrology problems.

Here the analysis of infiltration has proceeded for rigid soils by numerical solution of Equation 1. Examples include flux-controlled (rain) infiltration into uniform soil, infiltration into layered soils and into soils with nonuniform initial moisture content. Alternatively, infiltration under these conditions has been analyzed using quasi-analytical methods based on specific assumptions that simplify the mathematical solutions. One example, based on the Green and Ampt (1911) assumption of a capillary tube soil model, is the study of Childs and Bybord (1969) on ponded infiltration in layered soils with the hydraulic conductivity decreasing for successively deeper layers.

For a fuller review of infiltration in non-homogeneous soil and under a variety of boundary conditions we refer to Fleming and Smiles (1975). Here, we proceed by listing a few simplified infiltration equations that are of current

interest and in which the equation parameters have physical significance.

**Concise Infiltration Equations**

(a) Philip (1957c) from his analysis of infiltration suggests that, to a good approximation, the infiltration rate,  $v$ , may be described by

$$v = \frac{1}{2} S t^{-1/2} + A \dots \dots \dots (5)$$

where, for short time,  $A$  is as in Equation 4, but at larger times  $A = K_1$ .

(b) Linearization of  $D(\theta)$ , such that the linear diffusivity,  $D_* = S^2/4 (\theta_1 - \theta_0)^2$  gives the dimensionless equation

$$2V = (\pi T)^{-1/2} e^{-T} \text{erfc } T^{1/2} \dots \dots \dots (6)$$

where  $V = (v - K_1)/K_1$  and  $T = K_1^2 t / \pi S^2$ , if we consider the hydraulic conductivity,  $K_0$ , at the initial moisture content,  $\theta_0$ , to be negligible. This is usually the case.

(c) If we replace  $D(\theta)$  by a delta function, i.e.  $D$  is assumed to be very large and constant over a small range of  $\theta_1$ , and negligible over the rest of the  $\theta$  range, we have, for the infiltration rate

$$2\pi T = \ln[(V/1 + V)] + 1/V \dots \dots \dots (7)$$

where  $V$  and  $T$  are as for Equation 6. A delta function solution implies the physical existence of an infinitely steep wetting front. The Green and Ampt (1911) solution is of this type.

The linear solution (Equation 6) fits the data best (Philip, 1969b; Talsma and Parlange, 1972), but Swartzendruber and Youngs (1974), from a comparison of the integral forms of Equations 5-7, consider all solutions to be reasonable. They contend that Equation 5 is much to be preferred for ease of computation, especially its capability to express  $t$  as a function of  $v$ , as well as vice versa. In contrast, Equation 6 can only express  $t$  explicitly as a function of  $v$ , while in Equation 7 the reverse is true and the mathematical form is rather more complicated. However, Equations 6 and 7 both represent unique curves from which actual values of  $v$  are easily derived by using measured values of  $S$ , and a series of  $t$  values, in the expression for  $T$ .

The appeal of these simplified expressions for infiltration further rests on rapid and reliable field measurement of their parameters. These are the sorptivity,  $S$ , the hydraulic conductivity,  $K_1$ , and the parameter  $A$  in Equation 5. A very reasonable approximation, for infiltration at short times (up to half an hour for most rigid soils)  $A \cong \frac{1}{3} K_1$  (Philip, 1957c; Talsma 1969a). The field measurement and applicability of these parameters to watershed-runoff/infiltration models is discussed next.

### Field Measurements of S and $K_1$ , and Their Application

The simplest method of measuring sorptivity relies on the fact that during the early stages of infiltration (e.g. from a ring infiltrometer installed to some depth, say 10 cm) the first term in Equation 4 accounts for nearly all the flow (see Figure 2). This method is widely applicable, except where S is very small relative to  $K_1$ . This may occur in soils with high initial moisture content, resulting in small S, or where interconnecting large pores such as root channels give large values of  $K_1$  (Talsma, 1969a). In such cases, the analysis of three-dimensional flow from cavities (Talsma, 1970), where gravity effects are much reduced, provides a suitable alternative for measuring S *in situ*. Sorptivity can be measured rapidly using either method. Thus, replication may be used to help overcome spatial variability inherent in field studies.

Hydraulic conductivity,  $K_1$ , is easily obtained after excavation of the ring infiltrometers, by measuring the flow rate through the undisturbed sample in a field permeameter. Values so obtained, using sample dimensions of 30 cm diameter and 10 cm high, compare well with measurements using other techniques. The relatively large sample size helps to reduce variability in both  $K_1$  and S.

Some results of measurement of S and  $K_1$  with these methods are given in Figure 4. The data are from a small (2 x 5 m) relatively uniform field site. Variability of  $K_1$  is somewhat greater than for S, which is understandable since S varies as the square root of a length characteristic of the

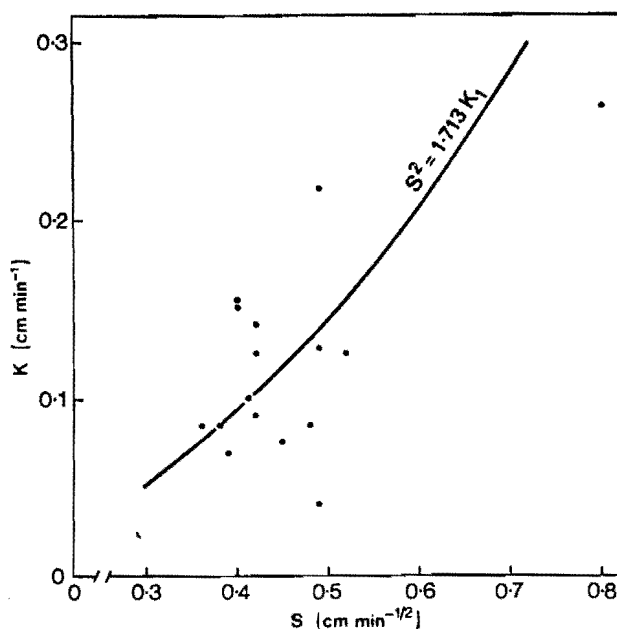


Figure 4. Small plot variability of hydraulic conductivity and sorptivity in a non-swelling soil (Barton loam).

porous medium and  $K_1$  as the square. The delta function approximation suggest the relationship between S and  $K_1$  to be  $S^2 = 2K_1(P + h)(\theta_1 - \theta_0)$ , where P = "wet front potential" in cm (as in the Green and Ampt model) and h = depth of ponded water (cm) over the surface. For this experiment, P = 1 cm, h = 2.5 cm, and  $\theta_1 - \theta_0 = 0.245$ . The suggested relation is then  $S^2 = 1.713 K_1$ . We observe (Figure 4), however, that the actual correlation between S and  $K_1$  is generally poor (see also Talsma, 1969a). Despite the rather large variability of both parameters, use of their average values predicted two-dimensional furrow flow very satisfactorily (Talsma, 1969b).

It is stressed that sorptivity is not a soil constant, but depends on initial moisture content,  $\theta_0$ , and depth, h, of ponded water in the infiltrometer. Sorptivity decreases rather strongly with increasing  $\theta_0$  (Philip, 1957b; Talsma, 1969a) and may also decrease significantly with decreasing h, where a soil contains many large interconnecting pores or root channels (Talsma, 1969a). In such soils, it is important to measure S at a ponding depth, h, appropriate to conditions for which its value is required. For example, the good agreement between predicted and observed infiltration in the two-dimensional furrow flow cited above (Talsma, 1969b) was undoubtedly due to the fact that water was ponded to the same depths in the infiltrometers and the furrows.

Sorptivity also varies with the imposed moisture content,  $\theta_1$ , at the soil surface (Table 2). Surface moisture contents may be much less than those resulting from ponding during rainfall at rates below the instantaneous ponding infiltration rate. Such conditions would frequently exist in watershed hydrology, and values of S may be greatly reduced (Table 2). Fleming and Smiles (1975) show that, approximately, Equation 5 and its integrated form can be solved to give an "equivalent time" to match the infiltration curve after ponding, under rainfall conditions, to that calculated from S and A values for ponding conditions. The concept "equivalent time" has been termed "time compression approximation (TCA)" by Reeves and Miller (1975).

The surface ponding method of measuring sorptivity is immediately useful in watershed studies where it is desired to investigate aspects of variability in infiltration conditions, such as might be caused by differing soil surface conditions. Some relevant data are shown in Table 3 for an experimental catchment on the Shoalhaven River in N.S.W. It is seen here that, as expected, bare surface

Table 3. Average sorptivities, S (cm min<sup>-1/2</sup>), for different surface conditions of an experimental catchment.

Surface Condition	Bare	Grassed	Tussocks
Moist (winter '69)	0.29	0.58	1.08
Dry (summer '69)	0.61	0.83	1.43

areas will produce runoff earlier than vegetated parts. The effect of initial moisture content on S is also apparent.

A further example of using S and  $K_1$  values measured with infiltrometers is provided by considering infiltration rates calculated from them together with rainfall intensity duration curves. This is shown for the A.C.T. in Figure 5. Infiltration rate curves for three major soil types are shown together with rainfall intensity-duration curves for short duration rainstorms, expected with frequencies of once in a 1, 5, and 20 years. Soil a is a gravelly loam in a native forest catchment of the Orroral Valley ( $\theta_0 = 0.10$ ; S, at incipient ponding, =  $0.80 \text{ cm min}^{-1/2}$ ;  $K_1 = 0.18 \text{ cm min}^{-1}$ ). Soil b represents permeable loams under improved pasture on hillslopes ( $\theta_0 = 0.10$ ; S =  $0.40 \text{ cm min}^{-1/2}$ ;  $K_1 = 0.12 \text{ cm min}^{-1}$ ). Soil c is a widely occurring yellow

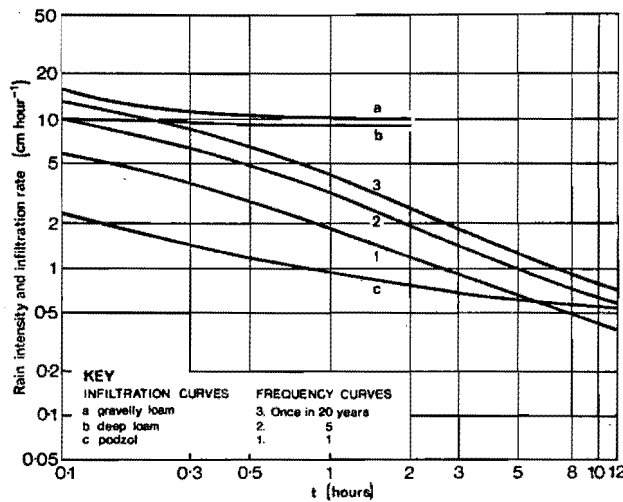


Figure 5. Rain intensity-duration curves in comparison with infiltration rate curves of three soils, for the A.C.T. Rainfall data from Anon. (1974).

podzolic soil ( $\theta_0 = 0.03$ ; S =  $0.17 \text{ cm min}^{-1/2}$ ;  $K_1 = 0.0084 \text{ cm min}^{-1}$ ). Infiltration rates were calculated using Equation 6.

Although the two sets of data are not directly comparable (e.g. the rainfall curves are plotted using statistically derived, time integrated intensities; the infiltration curves represent instantaneous rates valid only, at short t, for the initial moisture content specified; the rainfall rates do not accurately represent the temporal distribution (averages shown in Figure 6)) we may reasonably conclude that runoff is likely to occur frequently on soil c, infrequently on soil b and rarely, if ever, on soil a. This is in broad agreement with actual observation.

The values of S and  $K_1$  used for these soils are valid for the topsoil (20-30 cm), which can accommodate a typical summer rainstorm of 6 cm at the initial moisture contents specified. For rainfall of longer duration and quantity, soil inhomogeneity (especially decrease of  $K_1$  in the subsoil) needs to be considered.

The ring infiltrometer method of measuring infiltration may also be compared with methods estimating infiltration and runoff using portable sprinklers on small plots. Unpublished data of Fleming and Gifford (Fleming, personal communication), using rings and a Rocky Mountain infiltrometer, showed that results generally differed. However, final infiltration rates obtained with the technique of Costin and Gilmour (1970) were identical to values of  $K_1$  measured with ring infiltrometers on a grassed catchment in the A.C.T.

The rainfall simulator employed by Costin and Gilmour (1970) ensured even distribution of droplets falling with a terminal velocity ( $8 \text{ m sec}^{-1}$ ) closely matching that of actual rainfall, although median drop size (1.3 mm) was

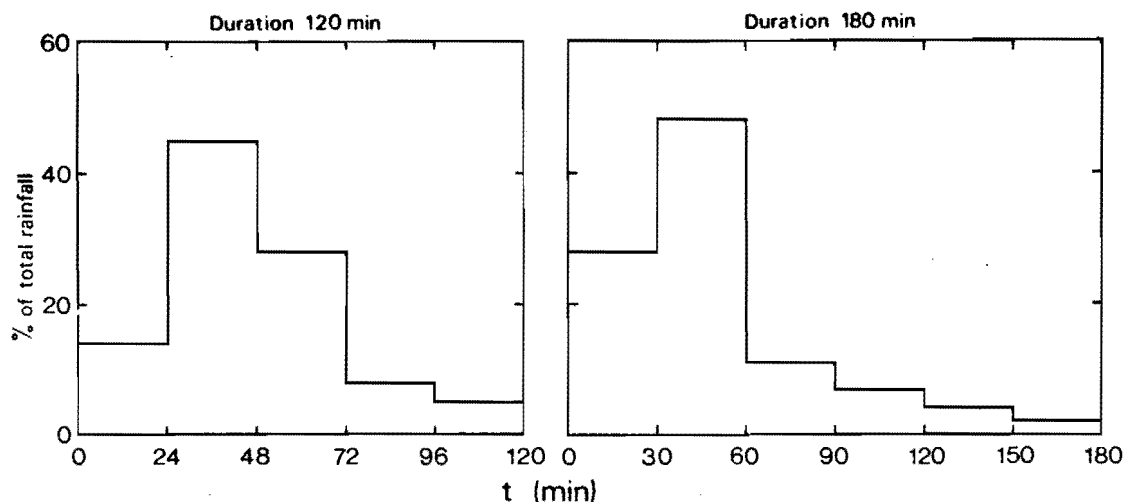


Figure 6. Temporal rainfall distribution (2- and 3-hour rainstorms) in the A.C.T. from Anon. (1974).

For example, drainage rates in a fine sand after 1 week of redistribution of 6 cm applied water were 0.07, 0.12 and 0.15 cm day<sup>-1</sup>, respectively, when this soil was at initial moisture contents ( $\theta_0$ ) of 0.015, 0.04 and 0.06. Here the decrease in  $d\theta_*/dz$  is more than offset by increases in both  $D_{\theta_*}$  and  $K_{\theta_*}$ .

From an applied viewpoint, note that redistribution and deep drainage continue for a considerable time. Hence, definition of "field capacity" as the amount of water retained in soil after "excess" has drained off during the first few days, or the specification of a specific value of moisture potential to characterize "field capacity" is erroneous. Drainage rates after 2 days in Figure 7b are still of the order of 2-4 cm day<sup>-1</sup> and 1.2 cm day<sup>-1</sup> after 1 week, where evaporation from the surface is prevented. The same order of magnitude of long term drainage rates has been found in field experiments on deeply-watered, covered plots (Talsma, in press).

Such rates of drainage represent a considerable accumulated loss of water to deeper layers, or to groundwater. However, these losses may not be very apparent from routine moisture sampling procedures, since the change of water content becomes very small after about 1 week of redistribution (0.003 day<sup>-1</sup> in Figure 7a between 1 and 2 weeks after redistribution).

#### Influence of Evaporation and Transpiration

While the study of water movement from covered plots gives considerable insight into the redistribution and deep drainage processes, and at the same time provides useful *in situ* methods for characterizing a soil's water transmission characteristics, the common field situation must include an evaluation of the effects of evaporation (from bare soil) and evapotranspiration (from cropped or naturally vegetated surfaces). Computer solutions of the combined effects of evaporation and redistribution on soil moisture movement are available, as well as diffusion analyses of the constant- and falling-rate phases of evaporation from bare soil. Talsma (in press) concluded from a review of such studies and from field data, that evaporation from bare, deeply-wetted soils affects redistribution to depth relatively little, whereas evapotranspiration from a crop or natural vegetation has a strong effect.

In the latter case, moisture withdrawal takes place over the depth of the root zone; in the former, the evaporation site is near the soil surface. Evaporation from bare soil may be further reduced by placing a mulch over the soil, thereby introducing a layer through which moisture moves in the vapor phase.

The combined effects of vegetation removal and mulching on the evaporation rate from Yandera loam with a water table at 157 cm depth may be deduced from the moisture potential distributions shown in Figure 8. Steady

state evaporation rates, calculated from Darcy's law and the moisture conduction properties (Figure 1), are about 0.40 and 0.20 cm day<sup>-1</sup> before and after removal of vegetation and surface mulching to 5 cm depth. The effect of changing the evaporation site in the soil reduced evaporation from 0.40 to 0.28 cm day<sup>-1</sup>, while the mulching effect of the shallow cultivated layer reduced evaporation further to 0.20 cm day<sup>-1</sup> (Talsma, 1963).

The effect of a mulch formed by cultivation on a non-swelling soil is only modest. Swelling soils often exhibit "self-mulching" characteristics that reduce evaporation more drastically. An example given in Talsma (1963) showed a reduction in evaporation from 0.17 cm day<sup>-1</sup> to 0.04 cm day<sup>-1</sup>. This is in contrast to prediction from swelling clay theory, where self-mulching is not considered (Philip, 1972).

We finally remark that redistribution to lower soil layers occurs less readily, where small amounts of water are applied. Here, evaporation is important. Furthermore, redistribution and drainage may be severely impeded by soil layering.

#### DEEP DRAINAGE AND GROUNDWATER FLOW

Some aspects of drainage losses beyond the immediate surface layers have already been discussed in Section 4. Figure 7a, for instance, shows that over 50 percent of initially applied water in this example ultimately leaves the initially wetted top-soil, while field data on deeply watered bare field plots indicate losses of up to 30 percent and on cropped plots up to 10 percent. Calculation of drainage fluxes (Figure 7b) necessitates detailed and time-consuming measurements of the basic soil hydrological properties. Soil heterogeneity further complicates the field situation. Where the overall magnitude of drainage in a catchment is of interest, rather than the detail of the process, it is customary to employ a water balance method. We discuss the results of two such studies.

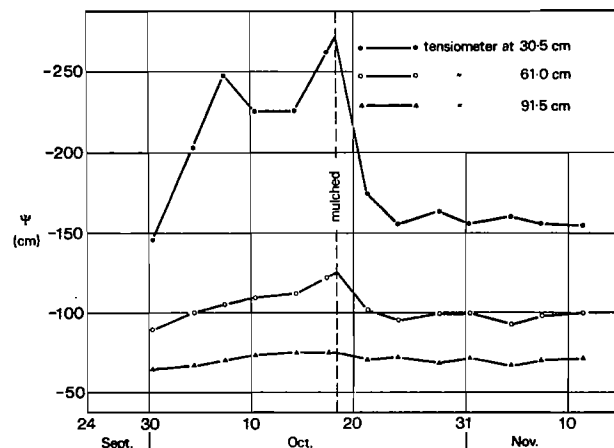


Figure 8. The effect of mulching and vegetation removal on subsoil moisture potential in Yandera loam.

considerably smaller than that of a typical rainstorm (2.3 mm). This matters little on vegetated sites but could, because of reduced splash impact energy, have considerable effect on a bare site.

The adaptation of the ring infiltrometer technique to measure  $S$  at arbitrary imposed moisture content,  $\theta_1$ , less than saturation, has not been attempted in Australia. However, a recent study of Dirksen (1975) in the USA indicates a suitable procedure for doing this. Dunin and Costin (1970) outline a method for obtaining  $S$  and  $K_1$  values from hydrographic analyses of runoff events from a large catchment.

**DISTRIBUTION OF SOIL WATER AFTER INFILTRATION**

**Redistribution Without Evaporation**

The prediction of redistribution of soil water after rain or ponded water disappears from the soil surface is basically a study of hysteresis. At the start of redistribution, drainage at different depths in the initially wetted profile starts along different scanning curves depending on the moisture content reached during wetting. Moisture profiles predicted from numerical solutions as well as observed profiles show distinct differences for different soils (Childs, 1969) and the rate of redistribution is dependent on initial moisture content as well as the amount of applied water (Peck, 1971; Talsma, 1974).

Figure 7 shows successive moisture profiles in a laboratory experiment on initially air dry loam, for various times up to 14 days after the addition of 10 cm of ponded water. Following Peck's (1971) numerical analysis, we note that at each depth in the soil during redistribution the moisture content,  $\theta$ , increases to a maximum value  $\theta_*$ , and then decreases. When the maximum moisture content,  $\theta_*$ , is at depth  $z = z_*$ , the soil is draining in the upper  $0 > z > z_*$  zone and wetting in the zone below  $z_*$ . The transition plane  $z = z_*$  moves downwards as redistribution proceeds. At any particular time,  $t_n$ , the drainage rate,  $q_*$ , from drainage to wetting zone may be calculated from Darcy's law

$$q_* = - \left[ D \frac{d\theta_*}{dz} \cdot K \right] \dots\dots\dots(8)$$

where  $D$  and  $K$  are the wetting values of moisture diffusivity and hydraulic conductivity at moisture content  $\theta_*$ , and  $d\theta_*/dz$  is the slope of the moisture profile at time  $t_n$  (at  $z = z_*$ ).

Figure 7b shows the rate of drainage across the transition plane as a function of redistribution time for the experiment shown in Figure 7a, as well as for two others at differing infiltration quantity,  $Q$ , and initial moisture content,  $\theta_0$ . We note that an increase in either  $Q$  or  $\theta_0$  for this soil results in lower rates of drainage. This is mainly due to a decrease of the moisture gradient  $d\theta_*/dz$ . Exactly the opposite is noted for redistribution in sand, where an increase in either  $Q$  or  $\theta_0$  increases the rate of drainage.

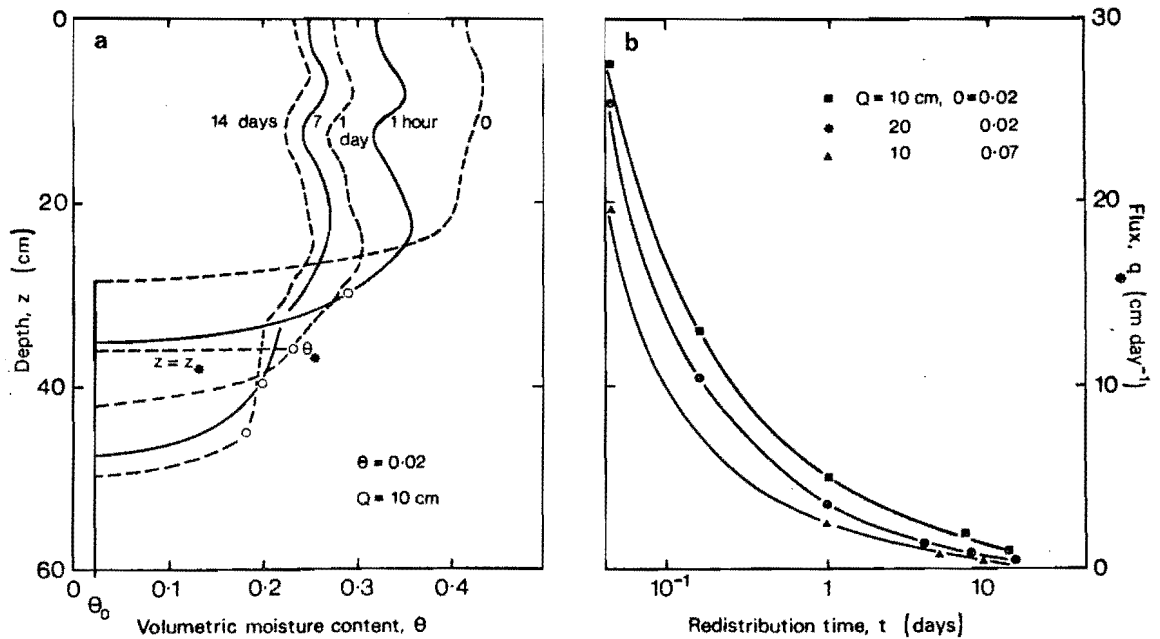


Figure 7. Redistribution in Glebe loam. (a) Depth/moisture content relations at various redistribution times. (b) Drainage flux/redistribution time relations.

At the land surface, the water balance is simply expressed by an equation such as

$$P = E + SD + UD + \Delta S \dots\dots\dots(9)$$

where P is rainfall or applied water, E is evaporation, SD is runoff or surface drainage, UD is underground drainage and ΔS is the change in water storage of the system, usually the change of soil water storage. All the terms in Equation 9 can be measured or, alternatively, one of the terms may be calculated once the others are known. Satisfactory estimates can be obtained where measurements are made over a sufficiently long time interval.

Table 4 shows the water balance of drainage lysimeters in grassland near Mount Gambier, South Australia, during three periods in 1963-1966. The area receives a predominantly winter rainfall and soils are deep sands underlain by clay. All components in Equation 9 were measured. The overall results over a 5 year period (Holmes and Colville, 1970a) gave a net drainage, to a watertable aquifer beneath, of 6.3 cm annually, or 10 percent of the mean precipitation. At the same location, there was no deep drainage to the aquifer under a *Pinus radiata* forest. Here evapotranspiration in winter and spring was more than double that of the grassland (Holmes and Colville, 1970b).

Another example is from the newly developed Coleambally Irrigation Area in south-western N.S.W. Here the introduction of irrigation is likely to result in changes in the groundwater hydrology of underlying aquifers, by the likely increase in the term UD in Equation 9. Before irrigation, underground drainage was zero over most of the area (Pels, 1968). Apart from canal seepage, the greatest possible contribution to UD is likely to come from rice, grown on fine textured clay soils under ponded conditions for about 120 days.

During this period, seepage losses may be simply estimated from the difference between cumulative infiltration, measured in large buffered infiltrometers, and soil moisture storage changes, measured either gravimetrically or by neutron attenuation. Losses beyond 3 m depth, estimated in this manner have varied from 2-30 cm over the 120 day ponding period, with a mean figure of about 10 cm (Talsma and van der Lelij, unpublished data). The higher losses occurred on uniformly fine textured swelling

clay soils, the lower rates on texture differentiated clay soils, where the impermeable B-horizon ( $K_1 = 0.018 \text{ cm day}^{-1}$ ) severely restricts downward movement.

The main aquifers in the region are under sub-artesian pressure, with pressure levels around 20 m below the ground surface. Overlying aquiclude materials have a storage coefficient of about 0.05, thus a 10 cm water loss beyond 3 m would raise the water table by 2 m. The annual rise of the water table in the region has been around 80-100 cm. The two figures are reasonably consistent considering that only some 30 percent of the area is intensively irrigated in any year.

Water transport in a water table aquifer, due to a stepwise change, ∇h, in water table height, h, may be calculated from

$$\nabla^2 h = \frac{\epsilon}{T} \frac{\partial h}{\partial t} \dots\dots\dots(10)$$

for appropriate boundary conditions. Here ε is specific yield and T is transmissibility of the aquifer. An example for annual recharge in south-western South Australia is given by Luthin and Holmes (1960). Water transport in a completely confined aquifer is more simply calculated from Darcy's law.

Disturbance of the natural hydrological water balance, such as induced by irrigation, or clearing of vegetation, may alter the groundwater hydrology over wide regions. This may be beneficial where groundwater remains fresh, but in semi-arid regions water quality often deteriorates along its flow path. As a consequence areas quite remote from the initial disturbance may suffer seriously from salinity. This subject will be treated in further detail by Peck.

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Table 4. Water balance of lysimeters in grassland near Mount Gambier, South Australia; surface drainage (SD) prevented (after Holmes, 1971).

Period	April '63 - April '64 (cm)	April '64 - March '65 (cm)	March '65 - January '66 (cm)
Rain, P	49.3	83.6	58.0
Evaporation, E	45.3	68.2	51.4
Drainage, UD	4.0	13.4	7.2
Storage, ΔS	0	2.0	-0.6

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# Evapotranspiration—Some Growth Areas

C. W. Rose\*

## INTRODUCTION

The framework of this paper is first to discuss in the following two sections limiting cases within the broad ambit of evapotranspiration problems: In section "Evaporation From Bare Soil Using Soil Measurements" methods of determining evaporation from essentially bare soil are considered, when the measurements are restricted to the soil itself. In section "Transpiration From Single Plants" a simple model which allows the transpiration from single or isolated plants to be simulated through time, given certain empirical relationships and meteorological data, is developed and illustrated.

Aspects of evapotranspiration of greater generality are taken up in section "Evapotranspiration," including methods of studying effects of land use or management changes on watershed hydrological characteristics. An example of a particular challenge to future research is given in section "A Challenge to Future Research: Predicting Soil Drying From Meteorological Screen Measurements."

Tanner (1967) reviews the methods used to estimate evapotranspiration.

## EVAPORATION FROM BARE SOIL USING SOIL MEASUREMENTS

### Determining Evaporation From Soil Profile Measurements

When water transport in the soil is not limiting evaporation, the evaporation rate depends entirely on the net energy available for evaporation and on factors determining the flux of water vapor in the atmosphere (Deacon, Priestley and Swinbank, 1958). The evaporation rate is then essentially that from a saturated surface, and the theory of Penman (1948, 1956) or Ferguson (1952) for the prediction of evaporation from open water surfaces using meteorological data may be applied to this problem

with reasonable accuracy. However, this approach is completely inapplicable when evaporation is limited by water transport in the soil (Stanhill, 1965; Philip, 1957), as is normally the case in range catchments.

A general method of estimating the evaporation which has taken place over a given time period  $t_1$  to  $t_2$  at a particular location is to measure profiles of volumetric soil water content ( $\theta$ ) at these times and apply the principle of mass conservation of water to the volume of soil contained between unit area of the soil surface and the depth of measurement  $z$ . The sign convention is that vertical distance  $z$  is positive measure **away** from the soil surface. It is consistent with this convention for fluxes **away** from the soil surface to be positive, and this is followed except for net radiation  $R_N$  and precipitation  $P$ , which are regarded positive to the soil surface.

From Figure 1 it follows that:

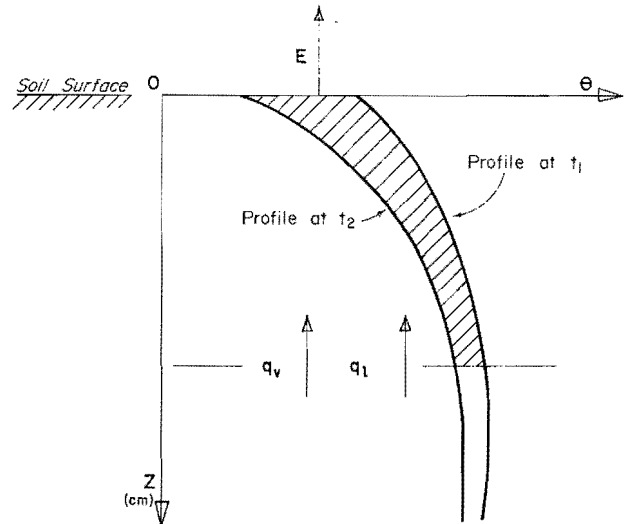


Figure 1. Illustrating how evaporation over the time period between successive measurements of water content profiles can be estimated. Term  $(\Delta M)_{0z}$  in Equation 1 is shown hatched.

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$$(1/\rho_l) \langle E \rangle (t_2 - t_1) + (\Delta M)_{oz} + (1/\rho_l) \int_{t_1}^{t_2} (q_l + q_v) dt = 0 \quad \dots \dots (1)$$

where:

- $\langle E \rangle =$  mean evaporation rate over time interval  $(t_2 - t_1)$  (in units of mass per unit area and time)
- $(\Delta M)_{oz} =$  increase in storage of water for depth interval 0 to  $z$ , over time interval  $(t_2 - t_1)$  (so  $-(\Delta M)_{oz}$  is the decrease)
- $= \int_{t_1}^{t_2} \int_0^z (\partial\theta/\partial t) dz dt$
- $\rho_l =$  density of water
- $q_l =$  liquid flux density at depth  $z$
- $q_v =$  water vapor flux density at depth  $z$

If follows from Philip and de Vries (1957) that liquid flux  $q_l$  is given by:

$$q_l/\rho_l = -D_{\theta_l} (\partial\theta/\partial z) - D_{T_l} (\partial T/\partial z) + K \quad \dots (2)$$

where  $D_{\theta_l}$  and  $D_{T_l}$  are isothermal and thermal liquid diffusivities derived and defined by Philip and de Vries (1957);  $K$  is hydraulic (or capillary) conductivity.

Vapor flux density  $q_v$  may be written as:

$$q_v/\rho_l = -D_{\theta_v} (\partial\theta/\partial z) - D_{T_v} (\partial e_s/\partial z) \quad \dots \dots (3)$$

where isothermal ( $D_{\theta_v}$ ) and thermal ( $D_{T_v}$ ) vapor diffusivities are as derived and defined by Rose (1968a).

Rose (1968a, b) has shown that field observations of varying water content and temperature profiles can be interpreted in terms of the transport Equations 2 and 3 (provided osmotic effects are not large). It was also found that when temperature gradients are large (e.g.  $> 0.5^\circ\text{C cm}^{-1}$ ), transport of water in the vapor phase can be comparable with that in the liquid phase, even at soil water suctions as low as 200-300 cm water. Rose (1968c) has applied Equations 1, 2, and 3 to calculate evaporation from bare soil, (Figure 2). Some unknown amount  $X$  of evaporation took place between wetting and the commencement of measurements.

Determining the diffusivity characteristics involves significant labor. However, in a range situation, provided sampling depth  $z$  (Figure 1) is not too small, frequently fluxes across it may be sufficiently small to neglect this term in Equation 1. A depth  $z$  of 30 cm (at which the temperature gradient due to the diurnal wave is negligible) ensures that  $q_v$  is small. A soil water suction not less than

about 3 bars would commonly result in a small value of  $q_l$ . Even if these requirements are net cumulative fluxes over periods of a month or more may still be significant.

**Isothermal Evaporation**

Under conditions of lower radiation, soil temperature gradients can be sufficiently low for vapor fluxes to be small and isothermal theory of water fluxes to be validly applied. Such theory will now be used to show how evaporation from a homogeneous soil can be estimated solely from measurements of soil surface water content ( $\theta_0$ ) which is easily determined. The field capacity ( $\theta_f$ ) and diffusivity ( $D(\theta)$ ) characteristics of the soil are also required.

Figure 3 shows the situation to be analyzed, where  $\theta = \theta_f$  at some indefinite depth, and  $\theta_0$  is a measured function  $\theta_0(t)$  of time. In these conditions it is reasonable

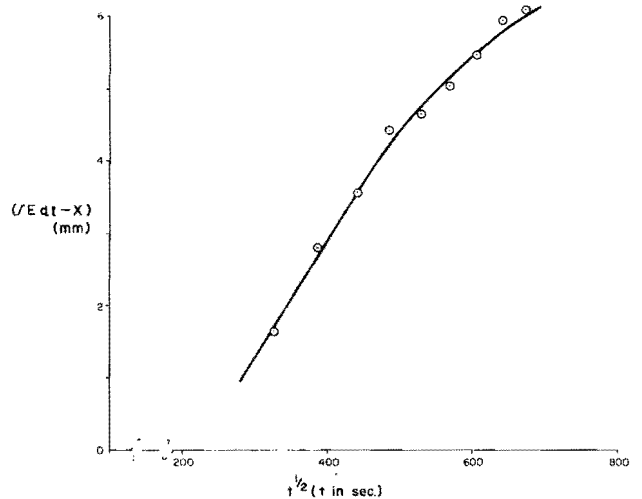


Figure 2. Estimated cumulative evaporation in the field from bare soil under conditions of high daily radiation. (Data from Rose, 1968c).

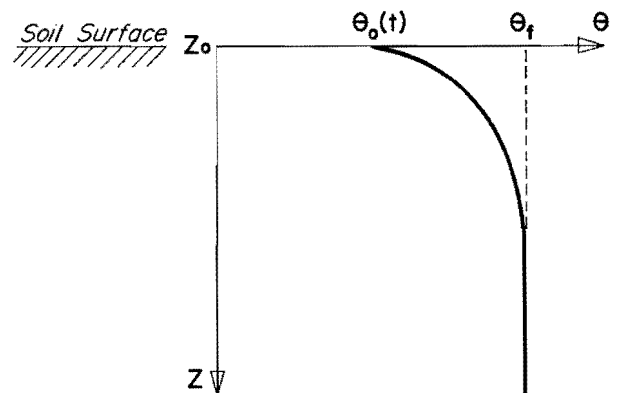


Figure 3. A water content profile formed by isothermal evaporation following an initial condition when  $\theta = \theta_f$  for all depths.

to assume that the influence of gravity is negligible. Following this assumption, the equation describing one dimensional water movement in soil (using the "inverted" form of Philip (1957)) is then:

$$\frac{\partial z}{\partial t} + \frac{\partial}{\partial \theta} \left( \frac{D(\theta)}{\partial z / \partial \theta} \right) = 0 \quad \dots\dots\dots(4)$$

The approach introduced by Parlange (1971 a, b) to solve this equation for constant concentration type boundary conditions will now be applied to this time-variable boundary condition problem of evaporation.

Integrating Equation 4 with respect to  $\theta$ :

$$\int_{\theta}^{\theta_0} \frac{(\partial z)}{(\partial t)} d\theta + \left. \frac{D(\theta_0)}{\partial z / \partial \theta} \right|_{\theta_0} - \frac{D(\theta)}{\partial z / \partial \theta} = 0$$

Surface flux  $\left. \frac{D(\theta_0)}{\partial z / \partial \theta} \right|_{\theta_0}$  is equal to

evaporation rate  $E$  (a function of time only), and as shown by Crank and Henry (1949a, b) the flux is approximately constant for  $\theta$  close to  $\theta_0$ . Thus a good approximation is that:

$$\frac{D(\theta)}{\partial z / \partial \theta} = E$$

and hence:

$$\int_{\theta}^{\theta_0} D(\theta) d\theta = \int_z^{z_0} E dz = (z_0 - z) E(t)$$

Thus 
$$z = \frac{1}{E} \int_{\theta_0}^{\theta} D(\theta) d\theta + z_0 \quad \dots\dots\dots(6)$$

and 
$$\frac{\partial z}{\partial t} = \frac{(dE/dt)}{E^2} \int_{\theta_0}^{\theta} D(\theta) d\theta + \frac{1}{E} \frac{d\theta_0}{dt} \quad \dots\dots(7)$$

From above, conservation of mass of water in the region  $\theta_0$  to  $\theta_f$  requires that:

$$\int_{\theta_f}^{\theta_0} \frac{(\partial z)}{(\partial t)} d\theta + \left. \frac{D(\theta_0)}{\partial z / \partial \theta} \right|_{\theta_0} = 0 \quad \dots\dots\dots(8)$$

Substituting for  $(\partial z / \partial t)$  from Equation 7 into 8 and rearranging leads to:

$$\frac{dE}{dt} = \frac{E \frac{d\theta_0}{dt} D(\theta_0) (\theta_0(t) - \theta_f) - E^3}{\int_{\theta_{0(t)}}^{\theta_f} (a - \theta_0(t)) D(a) da} \quad \dots\dots\dots(9)$$

In the denominator of Equation 9, which is simply a function of time,  $a$  is a dummy variable.

With  $\theta_0(t)$  measured and  $D(\theta)$  known, the ordinary differential Equation 9 can readily be solved numerically for evaporation rate  $E(t)$ . (Note that from Equation 6,  $z$  may be calculated as a function of  $\theta$  when  $E$  is known, and hence the complete water content profile at any time is also available from the solution.)

Lacking suitable isothermal field data to demonstrate the method proposed above for determining evaporation through time, the method was illustrated by assuming an initially uniform profile of water content ( $\theta = \theta_f$ ), and (somewhat unrealistically) that  $\theta_0(t)$  declined from  $\theta_f$  linearly with time. Solution of Equation 9 showed first an increase in  $E(t)$  associated with steepening gradients in  $\theta$ . This was followed by the commonly observed decline in  $E(t)$  as  $\theta$  decreased caused by the rapid fall in  $D(\theta)$  outweighing the effect of steepening gradients.

This analysis has been given in some detail both because of the practicality of this newly proposed method, and the general utility of applying Parlange's approach to solving the very nonlinear diffusion equation (despite the lack of convergence of proposed higher successive approximations (Knight and Philip, 1973)).

It may be noted that the method of Parlange effectively transforms the differential equation from partial (Equation 4) into ordinary form (Equation 9), and that although Equation 9 requires numerical methods to evaluate  $E$ , the whole solution is essentially analytical in character.

**TRANSPIRATION FROM SINGLE PLANTS**

In arid rangelands browse shrubs and trees provide significant forage, and are often at such a spacing that they should be considered as single or isolated plants. This section outlines a simple lumped-parameter model for water transport from soil to atmosphere through a single plant. Lacking suitable data on range plants, the illustrative relationships used in this section are for cotton (Rose, Byrne and Hansen, unpublished), but there is evidence that the general characteristics of the model are not specific to a particular species, or even to isolated plants.

Transpiration is ultimately chiefly controlled by the largest resistance to water transport through soil and plant, which is the diffusive resistance of stomata to water vapor (Rawlins, 1963). This resistance is generally related to the water potential in the leaf ( $\Psi_l$ ). Potential  $\Psi_l$  in turn depends on soil water potential ( $\Psi_s$ ) and the sum ( $R_s + R_p$ ) of resistances to water flow in soil and plant respectively.

Using this analog of Ohm's law (van den Honert, 1948) as a lumped-parameter model of the transpiration stream (of rate  $T$ , positive if lost by the plant) leads to:

$$\Psi_l = \Psi_s - T(R_s + R_p) \dots\dots\dots(10)$$

Partitioning the resistance sum into its components  $R_s$  and  $R_p$  is still somewhat in dispute. Although it is generally agreed that  $(R_s + R_p)$  increases significantly as water stress increases, some authors ascribe this increase wholly to  $R_s$  (e.g. Gardner and Ehlig, 1962) or almost wholly to  $R_p$  (e.g. Newman, 1969). Evidence is accumulating that the resistance in either pathway can be important in different situations.

Regardless of the outcome of this controversy, progress can be made towards a usefully predictive model by noting that from measurements on a wide range of plant species, at least two relationships of a generally similar character emerge, namely:

$$(R_s + R_p) = f_1(\Psi_x) \dots\dots\dots(11)$$

illustrated in Figure 4, and

$$\frac{T}{T_m} = f_2(\Psi_x) \dots\dots\dots(12)$$

illustrated in Figure 5, where  $T_m$  is the maximum transpiration rate under the particular environmental conditions, corresponding to minimum stomatal resistance. Since water potential was measured in the xylem ( $\Psi_x$ ) rather than in the leaf ( $\Psi_l$ ) in these experiments, the former potential is used in Equations 11 and 12. The relationships are expected to be very similar whether  $\Psi_l$  or  $\Psi_x$  is used.

Substituting from Equations 11 and 12 into Equation 10 gives the relationship:

$$\Psi_x = \Psi_s - T_m f_2(\Psi_x) f_1(\Psi_x) \dots\dots\dots(13)$$

Equation 13 can be employed as a lumped parameter model describing the dynamics of transpiration provided that the experimentally determined relationships  $f_1(\Psi_x)$  and  $f_2(\Psi_x)$  are generally applicable, and the  $\Psi_s$  and  $T_m$  are known or separately obtained. To obtain  $\Psi_s$  this model would need to be linked with another model applying mass conservation considerations to water within the root zone of the plant (e.g. Fitzpatrick and Nix, 1969; Rose et al., 1972a,b), giving an "effective" value of  $\Psi_s$  for the root profile.

Whilst  $T_m$  would be approximated by "potential evapotranspiration" for a continuous sward, the best method of estimating  $T_m$  for an isolated plant in the field is uncertain. Two possible methods of estimation are as follows:

- (i) If air at temperature  $T_a$  is brought to the isolated plant at wind speed  $u$ , the maximum heat energy which could be used for transpiration may be calculated by assuming the air leaving the vegetation has been cooled to the appropriate wet bulb temperature,  $T_w$ . Denoting the

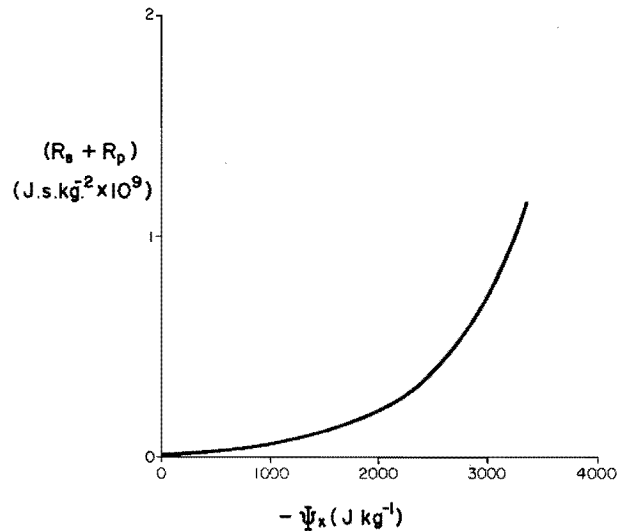


Figure 4. Form a relationship between resistance sum ( $R_s + R_p$ ) and  $\Psi_x$  for cotton plants [Rose, Byrne, and Hansen, unpublished].

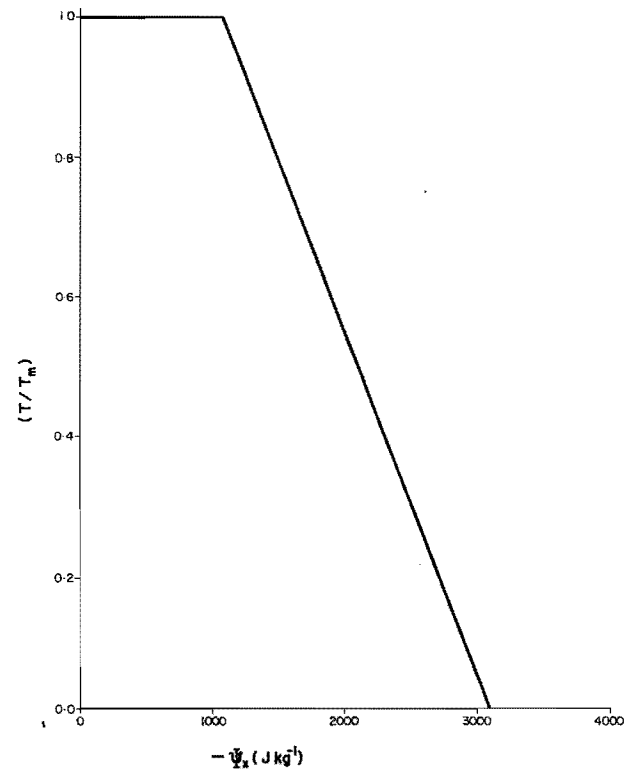


Figure 5. The relationship of Equation 12 for cotton plants (Rose, Byrne, and Hansen, unpublished).

area of the plant when viewed horizontally as  $A_h$ , this approach leads to an estimate for  $T_m$  of:

$$T_m = c_p \rho_a A_h u (T_a - T_w) / L$$

where  $c_p$  and  $\rho_a$  are the specific heat at constant pressure and density of moist air, and  $L$  the latent heat of vaporization of water.

(ii) A second method of estimating  $T_m$  would be to estimate  $H$ , the sensible heat flux density into the air, and assume this is intercepted by the plant of plan area  $A_p$ , and the energy  $HA_p$  transformed into transpiration given by:

$$T_m = H A_p / L$$

(If isolated plants were sparse,  $H$  could be estimated from energy balance considerations given in section "Conservation Principles").

Thus, the only unknown  $\Psi_x$  can be found by solving Equation 13, which, since it is implicit in  $\Psi_x$ , requires iterative or graphical methods.  $T$  is then available from Equation 12. Using the symbol conventions of Forrester (1968), Figure 6 represents the model.

Figure 7 shows some results of simulation of a uniform drying cycle with the model when  $T_m$  was taken as zero at night and given the typical diurnal variation evident on day 1. The midday depression in  $T$  on day 5 is caused by a rapid decline in  $\Psi_x$  (and so increase in  $(R_s + R_p)$ ) during this period of the day. Below a certain level of available water content, the simulation indicates an approximately linear decline in transpiration (expressed as a fraction of the maximum or potential value). These and other features of the simulation have been observed in the field.

Since qualitatively similar relations to those shown in Figures 4 and 5 have been obtained for a range of species (e.g. Hansen, 1971; Stoker and Weatherley, 1971), it would seem to follow that the qualitative features of this model may have significant generality. The nonlinear and approximately exponential increase in  $(R_s + R_p)$  with

declining  $\Psi_x$  (Figure 4) would superficially appear to favor plant survival by conserving more water reserves than if this feature were absent.

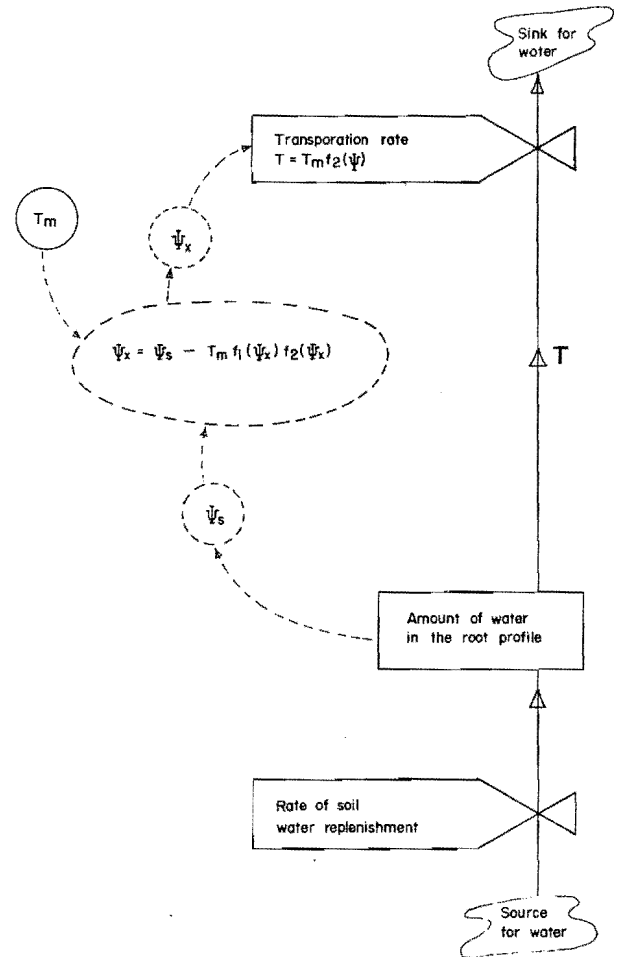


Figure 6. A continuous system-type representation of the lumped-parameter model of transpiration here described.

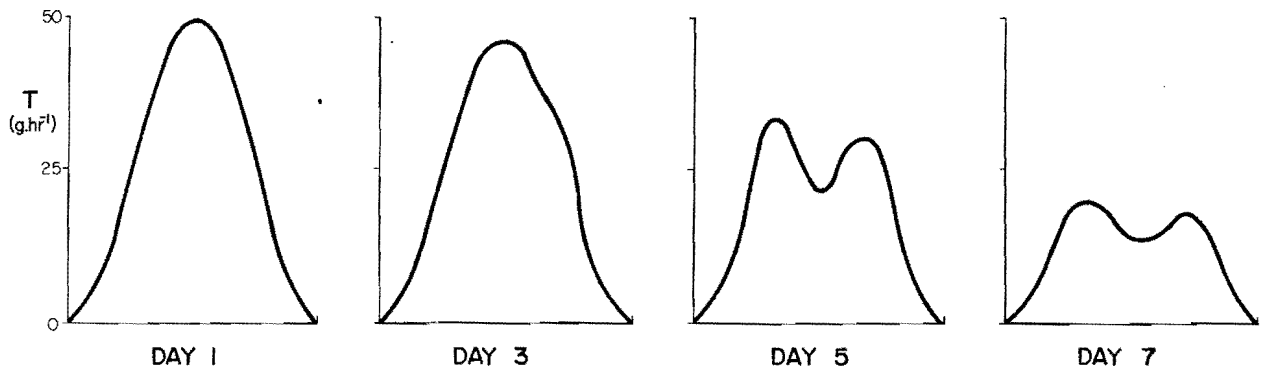


Figure 7. Diurnal patterns of transpiration during a drying cycle predicted by the model here described.

### EVAPOTRANSPIRATION

Methods of estimating evapotranspiration from any land surface, whether fully, partially or non-vegetated, and whether at macro- meso- or micro-scale, depends on basic physical principles of mass or energy conservation.

#### Conservation Principles

With the sign conventions given in section "Determining Evaporation From Soil Profile Measurements," energy conservation within unit area of a vegetated layer requires that:

$$R_N = H + LE + G + V \dots\dots\dots(14)$$

where the flux densities refer respectively to net radiation, sensible, latent, and soil heat fluxes, and V is the rate of increase of energy stored within the vegetated layer (a term of more significance for a forest than a pasture for example — Rose et al., 1972a).

Secondly, applying the principle of conservation of mass to a volume of soil of unit surface area and specified depth which receives precipitation P over a particular period of time requires:

$$P = fEdt + U + \Delta M + \Delta D + S \dots\dots\dots(15)$$

where U is the net flux out of the volume considered into adjacent soil; ΔM the increase in soil water storage; ΔD the increase in surface detention and interception, and S net surface run-off.

Finally, applying the conservation principle to the heat energy in a given volume of air in contact with the ground (Figure 8) it follows that:

$$E_o + H_o = E_z + H_1 + dQ/dt \dots\dots\dots(16)$$

where the fluxes are defined in Figure 8, and (dQ/dt) is the rate of increase of heat energy stored within the volume. The flux difference (H<sub>1</sub> - H<sub>o</sub>) is called the horizontal advective flux.

#### Measuring Evapotranspiration Using the Mass Conservation Equation

Equation 15 can clearly be adapted and applied at any scale, including that of a hydrologically defined watershed or catchment (Penman, 1963). On this scale it has been used to examine the hydrological effects of changes in land use or watershed management, such as the effect on streamflow of developing softwood plantations in bamboo forest in Kenya (EAAFRO, 1962).

In studying watersheds Equation 15 is typically applied over a "hydrological year" chosen so that not only ΔD but ΔM is very small compared to other terms.

If the underlying geological structure or soil in the watershed is impermeable then U = 0, and so evapotranspirations Edt can be calculated by measuring S using stream gaging, and P using a number of precipitation gages, where the number of gages is dependent on the catchment size, and the catchment and rainfall characteristics.

It is possible to check whether or not U is zero by an adequate program of soil moisture sampling. The approach used by EAAFRO (1962) in high rainfall tropical watersheds in Kenya is as follows: The soils were very deep, well-drained latosols of high water storage and infiltration capacity. On these soils there is little if any surface run-off so that when Equation 15 is applied on a per unit area basis, S = 0.

Applying Equation 15 over a hydrological year on a catchment basis, and providing U = 0:

$$fEdt = P - S \dots\dots\dots(i)$$

Define the ratio f as:

$$f = (fEdt/fE_o dt) \dots\dots\dots(ii)$$

where E<sub>o</sub> is the evaporation rate from an open water surface (a known quantity, measured by evaporation pan). Combining (i) and (ii),

$$f = (P - S)/E_o dt \dots\dots\dots(iii)$$

Note that if U ≠ 0, then f from (iii) will be an overestimate.

Due to the fact that water is freely available throughout the year, and as these catchments were close to the equator, fraction f was likely to be virtually constant at all times of the year (although this would not be true in general).

Applying Equation 15 on a unit area basis (so that S = 0), ΔM was then calculated for successive 10-day periods from:

$$\begin{aligned} \Delta M &= P - fEdt \\ &= P - f f E_o dt \dots\dots\dots(iv) \end{aligned}$$

which continues to assume U = 0.

The deep soil profile was considered divided into a root zone and below this a region where water could be temporarily stored whilst in transit to streamflow. If ΔM calculated from (iv) was greater than ΔM<sub>f</sub>, the amount of water required to bring the root zone to field capacity, then it was partitioned:

$$\Delta M = \Delta M_f + \Delta S \dots\dots\dots(v)$$

where if further water in addition to  $\Delta M_f$  was available, this was placed in temporary storage,  $\Delta S$ , which, after due time delay, would be expected to contribute to streamflow  $S$ .

In situations where  $U > 0$ ,  $f$  is overestimated, and therefore  $\Delta M$ ,  $\Delta M_f$  and possibly  $\Delta S$  are underestimated. Furthermore, if  $U \neq 0$ , error introduced into calculated values of  $\Delta M$  would tend to accumulate with time, at least until  $\Delta M > \Delta M_f$ . Error in  $\Delta S$  would accumulate indefinitely.

The EAAFRO workers compared the water storage measured in the root zone with the same quantity calculated as above over a period of several years, and found no consistent divergencies. They also compared the sum of  $\Delta S$  values over a hydrological year, and found no accumulating discrepancies with streamflow measurements accumulated over the same period. They therefore concluded that the catchments in which they were working were "watertight" (EAAFRO, 1962). However had such divergencies accumulated, such divergencies could also have been used to

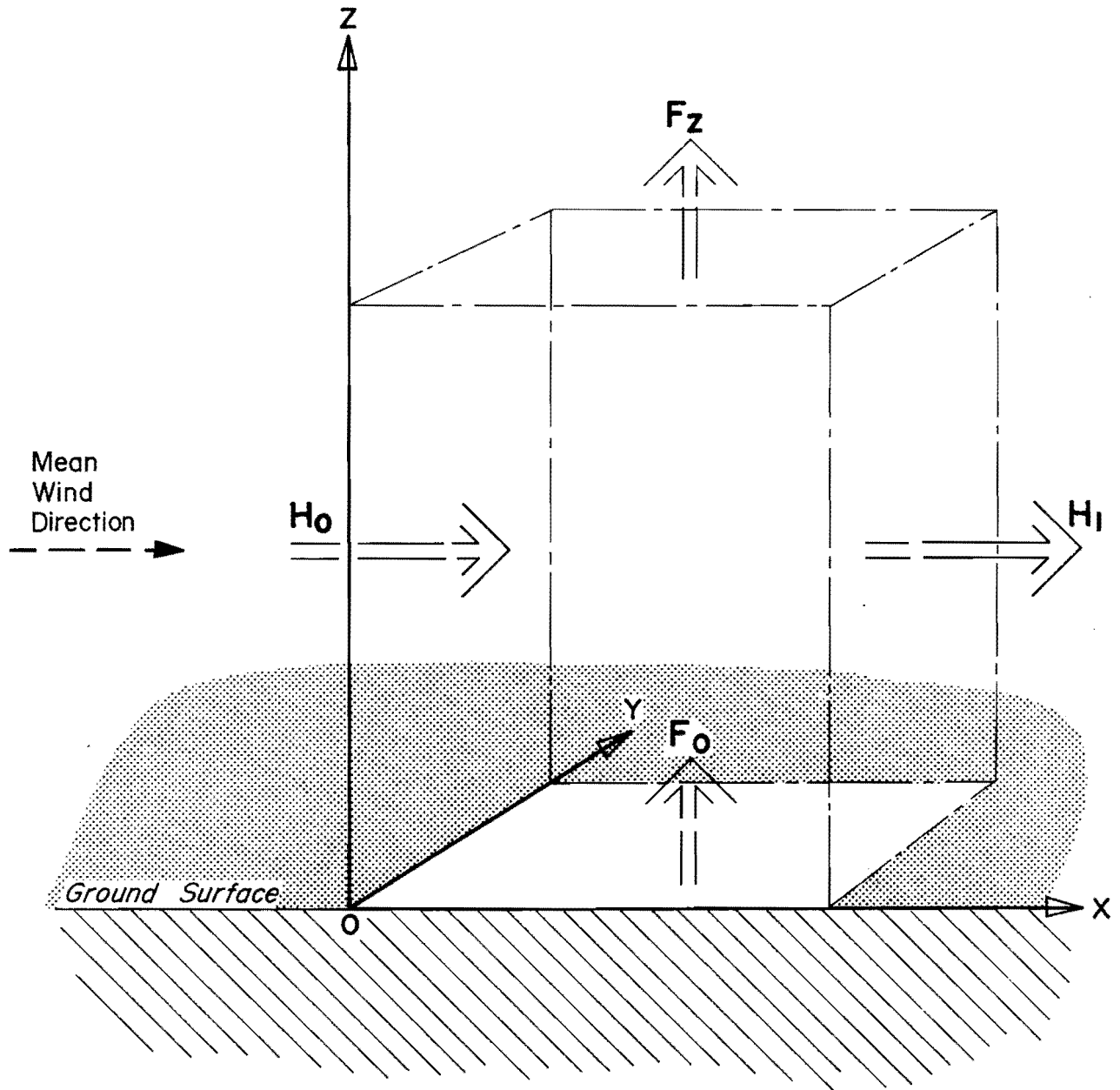


Figure 8. The broken lines define a rectangular region in space, fixed with respect to the ground surface through which air can flow unhindered. The unit area of ground surface shown in the x-y plane provides the lower boundary to the region.

estimate  $U$ , since the value of  $f$  which gave no long term divergencies would be:

$$f = (P - S - U)/E_0 dt$$

Some of the assumptions described above were appropriate only to the particular watersheds. However this more intensive style of approach, in which a running water budget for soil moisture is obtained, will in general lead to a more rapid and accurate assessment of the effect of changes in land use or management on watershed hydrology than the measurement of rainfall and stream-flow alone. Objectives of watershed management may often change too quickly for the latter more classical approach to be effective!

#### Combination of Energy Conservation and Atmospheric Profile Methods

This family of methods have chiefly been used where interest centers on shorter period information on evapotranspiration than emerge from the watershed approach outlined in the previous section. The method depends on the theory of steady-rate turbulent transport, which relates the mean energy or mass flux in the lower atmosphere to the appropriate concentration gradient.

A further assumption is that the transport is one-dimensional and vertical, thus with no horizontal gradients in temperature or humidity at the scale of measurement, which if present, would lead to horizontal advection (Figure 8). Horizontal gradients can arise if measurements are affected by an upwind region with different fluxes to those at the site of profile measurements. This is the problem of inadequate fetch. Horizontal gradients are also propagated above patterned vegetation (e.g. Mulga in the Australian arid zone), but are generally dissipated at heights approximately twice that of the patterned vegetation (Graetz, unpublished).

To obtain the evaporative flux one must also obtain the sensible heat flux. These fluxes are related to the vertical gradients in specific humidity  $q$  and air temperature  $T$  by:

$$E = -\rho_a K_w (\partial q/\partial z) \dots\dots\dots (17)$$

and

$$H = -\rho_a c_p K_H (\partial T/\partial z) \dots\dots\dots (18)$$

with the sign convention described in "Determining Evaporation From Soil Profile Measurements." Assuming the turbulent diffusivities  $K_w$  and  $K_H$  for water and heat energy are equal, the three unknowns  $K(=K_w$  or  $K_H)$ ,  $E$  and  $H$  can be solved from Equations 14, 17, and 18.  $K$  depends on a number of factors, including wind speed and height.

Figure 9 illustrates fluxes measured in both steady and nonsteady conditions above an extensive tropical pasture of Townsville stylo (*Stylosanthes humilis* H.B.K.) at Katherine, N.T., Australia (latitude 14.5°S, longitude 132.3°E). The instrumentation employed in such studies is considerable, and that used to obtain the data in Figure 9 is described by Byrne et al. (1971).

Since the theory employed assumes steady state conditions (i.e. cloud-free or continuous cloud), the micrometeorologically derived fluxes  $E_m$  and  $H_m$  were compared with independent measurements of  $E$  and  $H$  using a weighing lysimeter and "fluxatron" respectively. In these experiments agreement was generally within 6 percent under steady conditions, but under highly variable radiation, micro-meteorological techniques underestimated evapotranspiration by up to 18 percent when compared with measurements by weighing lysimeter over a period of nearly a day (Rose et al., 1972a).

Apart from such possible errors, the considerable experimental effort involved in such methods limit their utility, unless the instrument performs on-line computation allowing integrated totals over longer time periods to be read (as in the case of the "fluxatron").

#### Evapotranspiration Models

The continuous water balance accounting described in section "Measuring Evapotranspiration Using the Mass Conservation Equation," and also developed by Slatyer (1960) and Fitzpatrick and Nix (1969) illustrate the practical utility of formalized conceptual models.

Figure 10 is the flow chart of a model which simulates water content profiles from rainfall and pan evaporation data (Rose et al., 1972b). In climates where temperature is not a limitation to plant growth, this model goes further to illustrate how the conceptually expected, and experimentally determined, relationships between water use and dry matter accumulation (as modified by nutrition) can be used to infer dry matter in seasons other than that in which the relation was developed. Testing such simulation against experimental results gives some confidence that the approach is of sufficient accuracy that it may be used with long term meteorological records to predict long term yield expectations of annual pastures. This enables the relationship between annual yield and its probability to be estimated (e.g. McCown, 1973), a relationship which is of economic importance, especially in an environment such as tropical Australia where drought imposes a major restraint on agricultural productivity.

#### A CHALLENGE TO FUTURE RESEARCH: PREDICTING SOIL DRYING FROM METEOROLOGICAL SCREEN MEASUREMENTS

Some methods of estimating evaporation from essentially bare soil were discussed specifically in section

"Evaporation From Bare Soil Using Soil Measurements," the methods of section "Evaporation" being of general application.

One of the significant challenges to research in evaporation from bare soils is to be able to predict it in the field (given soil hydraulic and thermal characteristics) from measurements (at say screen height) of air temperature, humidity and wind speed, with net radiation either measured or estimated. Rosema (1974) has achieved this objective using numerical methods to solve the relevant transport equations. Whilst this approach may be adequate, the author draws attention to computational difficulties associated with description of moisture (liquid

and vapor) transport near the soil surface. Such solution is very demanding on computational stability because very small grid intervals have to be used to represent the very high gradients, particularly in soil water potential, which exist near the soil surface.

The remainder of this section will be devoted to outlining an approach to the problem of predicting soil drying from the soil and meteorological information listed above. Essentially analytical methods of solution of water flux in the soil, related the method used in section "Isothermal Evaporation," would be expected to avoid the problem of computational stability using numerical approaches which was experienced by Rosema (*loc. cit.*).

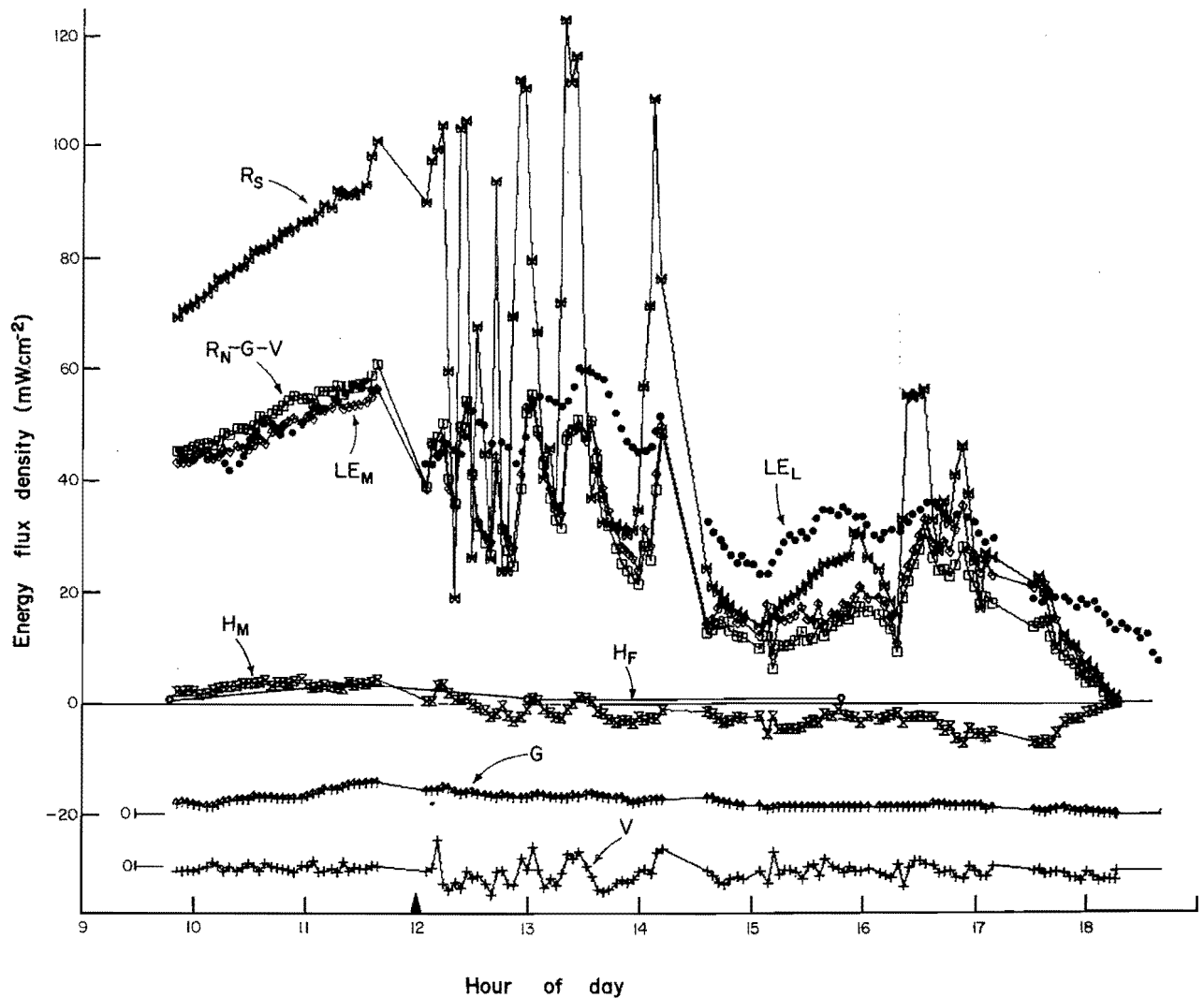


Figure 9. History of components of the energy balance equation for a Townsville stylo (*Stylosanthes humilis* H.B.K.) pasture at Katherine, N.T., Australia, on April 4, 1967.  $R_s$  is incoming solar radiation flux density,  $LE_L$  latent heat flux density derived from weighing lysimeter record,  $H_F$  sensible heat flux density measured by "fluxatron." Subscript M denotes micrometeorologically derived quantities. G and V as defined in Equation 14. Zeroes displaced  $-20 \text{ mW cm}^{-2}$  for G, and  $-30 \text{ mW cm}^{-2}$  for V.



Water and heat energy fluxes in soil and atmosphere are linked by conservation requirements applied to the soil surface. Energy balance at the soil surface is given by Equation 14 with  $V = 0$ .

The turbulent transport Equations 17 and 18 can be integrated with respect to height from ground ( $z = z_0 = 0$ ) to screen ( $z_a$ ) to give:

$$LE = c_1 h (e_0 - e_a) \dots\dots\dots (19)$$

and

$$H = c_2 h (T_0 - T_a) \dots\dots\dots (20)$$

where  $c_1$  and  $c_2$  are known constants,  $e$  vapor pressure,  $T$  temperature and  $h$  an energy transfer coefficient dependent on wind speed and atmospheric stability conditions (i.e. on  $H$ ).

The corresponding mass balance for water at the soil surface requires that:

$$q_0 = -E \dots\dots\dots (21)$$

where  $q_0 (=q_l + q_v)$  at  $z_0$  is the moisture (liquid plus vapor) flux in the soil at the surface.

An implicit assumption in Equation 14 (applied to the soil surface with  $V = 0$ ) is that evaporation takes place at the soil surface, as it does when the surface is wet. However, as evaporation proceeds, the site of evaporation quickly retreats below the soil surface to produce a relatively thin dry layer (Figure 11) in which the following assumptions are probably good approximations:

- (i) There are no vapor sources or sinks (i.e. site of evaporation is below this layer, and  $q_0 = q_v$ ).
- (ii) The water flux is entirely in the vapor phase.
- (iii) If the layer is defined by  $z_1 \leq z \leq 0$ , then  $z = z_1$ ,  $\theta = \theta_1$ , where if  $\theta < \theta_1$ , the relative humidity of soil air is less than unity.

Energy balance at the soil surface is then expressed by:

$$R_N = H + G_0 \dots\dots\dots (22)$$

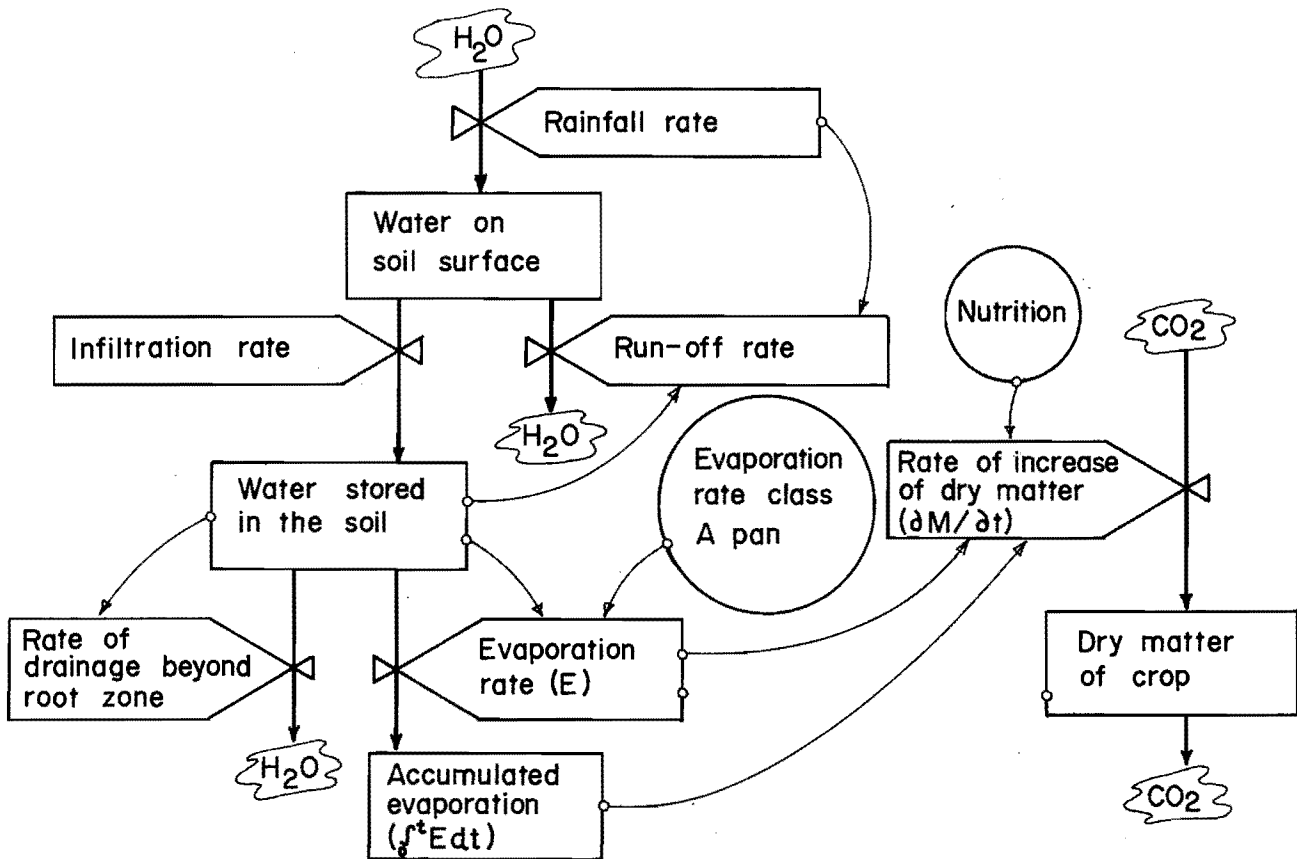


Figure 10. Generalized continuous system-type presentation of a model used to simulate evapotranspiration (and growth) of ungrazed Townsville stylo pastures (Rose et al., 1972b).

where the sensible heat fluxes in the soil, defined in Figure 11 are related by

$$\dot{Q} = G_0 - G_1 \quad \dots\dots\dots(23)$$

where  $\dot{Q}$  is the rate of increase of sensible heat storage in soil to depth  $z_1$ .

**Heat Transfer in Dry Layer**

The equation describing heat transfer in this thin dry layer is :

$$C \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \left( \lambda_* \frac{\partial T}{\partial z} \right) \quad \dots\dots\dots(24)$$

where C is soil heat capacity, T is temperature, and  $\lambda_*$  is the effective thermal conductivity of soil (a function of  $\Theta$ ).

Equation 23 is Equation 24 integrated across the depth of the thin layer (Figure 11).

**Moisture Transfer in Dry Layer**

Since the thin layer is characterized by the dominance of vapor transport, the equation describing moisture transfer in this layer is:

$$\frac{\partial}{\partial z} (q_v/\rho_v) = 0 \quad \dots\dots\dots(25)$$

where  $(q_v/\rho_v)$  is given by Equation 3. Integrating

Equation 25 across the thin layer:

$$q_v|_{z_1} = q_0 = -E \quad \dots\dots\dots(26)$$

**Main Layer**

As indicated in Figure 11, the soil profile has been divided into a layer of time variable thickness  $z_1$  with the characteristics described above, below which is what may be called a "main" layer. In this layer moisture fluxes may be in either phase, with the requirement of mass and energy continuity across  $z_1$ .

The methods of Parlange described in section "Isothermal Evaporation" shows promise of enabling essentially analytical solutions to be obtained for the coupled heat and moisture fluxes in both main and thin layers, which, when coupled with the transport equations in the atmosphere as Rosema (1974) has done, should enable more satisfactory solution of this most general problem of predicting how soil dries out.

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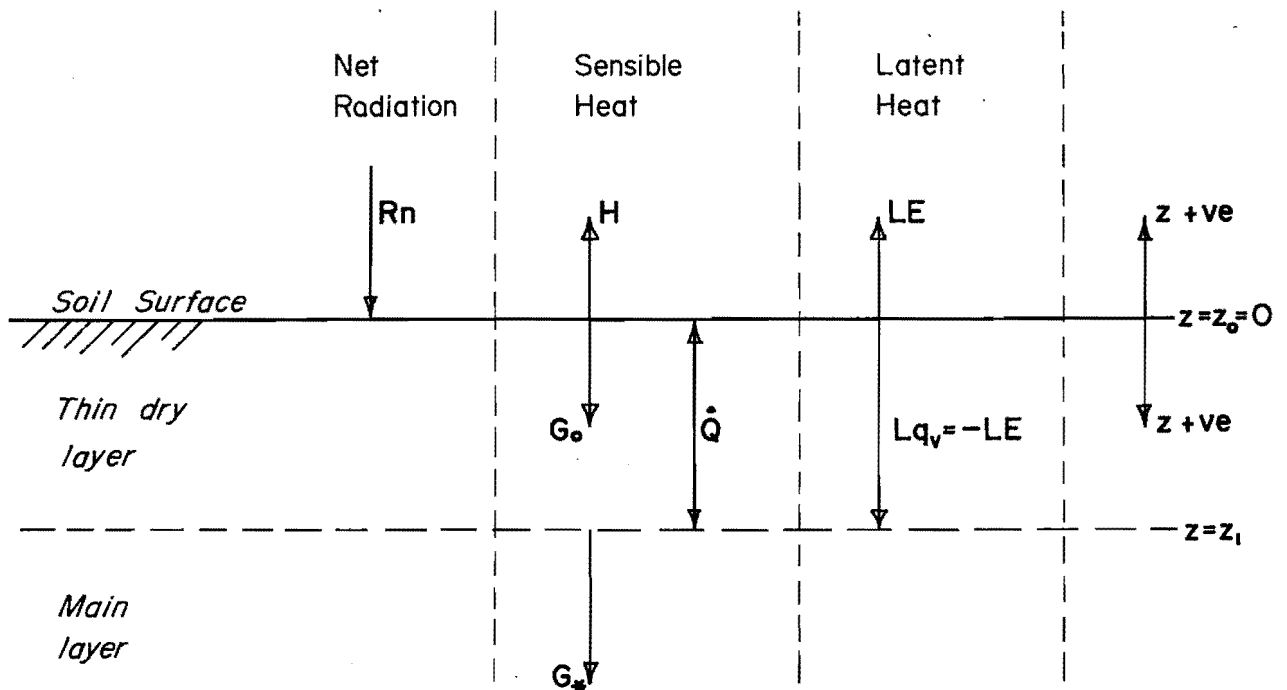


Figure 11. Energy flux densities at the soil surface and in the thin dry layer which forms under evaporation.

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# Hydrology: The State of the Science Evapotranspiration

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## INTRODUCTION

Studies of evapotranspiration have been conducted for more than 100 years. Yet, the concept of evapotranspiration originated with the precipitation-effectiveness ratio which was used at the beginning of this century to explain the distribution of forest centers in the Eastern United States (Transeau, 1905). The first working definition of potential evapotranspiration (consumptive use) was proposed by Thornthwaite (Wilm et al., 1944) as "the water loss which will occur if at no time there is a deficiency of water in the soil for the use of vegetation." Thornthwaite concluded that actual evapotranspiration may be the same as potential evapotranspiration during periods of large amounts of precipitation, but it is smaller during periods of less precipitation.

Since 1944 attempts have been made to clarify or to redefine potential evapotranspiration. Although Swinbank (1965a) suggested that "the concept of potential evapotranspiration was useless, in that it cannot be defined and it cannot be measured," it continues to be used to describe conditions for water loss to the atmosphere from plants, soil, and free water (Decker, 1966). The importance of evapotranspiration is realized when one recognizes that the equivalent of 4.5 million m<sup>3</sup> of water leaves the North American continent, in vapor form, every second (Roberts, 1969). Hamon (1966) reported that an average of 70 percent of the annual precipitation of the conterminous United States is returned to the atmosphere via evapotranspiration. In arid areas of the western United States, 90 percent of the annual precipitation is returned to the atmosphere through evapotranspiration. Evapotranspiration commonly removes  $45 \times 10^3$  kg of water from a hectare on soil of a warm, summer day (Decker, 1966).

As long as potential evapotranspiration measurements are used as a basis for climatic classifications, there are few difficulties, but when the concept is used to estimate plant water loss in arid areas, a number of difficulties arise (Stanhill, 1965; 1973). Actual evapotranspiration is difficult to evaluate since it is not only dependent upon atmospheric

conditions but also upon the amount of water available to the vegetation.

Although evapotranspiration, evaporation, and transpiration are often used interchangeably in the literature, more distinction should be made between the various processes. Stanhill (1973) suggested that the term evapotranspiration should be reserved for reference to total water lost to the atmosphere per unit ground surface. In this context, evaporation would refer to water loss from soil or from a free water surface and transpiration would refer to water vapor lost to the atmosphere through plant surfaces.

Excellent reviews have been published and symposia and seminars have been developed on the subject of evapotranspiration. Horton (1973) has compiled an extensive abstract bibliography covering research on evapotranspiration. Proliferation in research of evapotranspiration is being evidenced by the amount of literature available on the subject. This paper will present only selected references relating to the state of the knowledge of evapotranspiration.

## METHODS OF ESTIMATING EVAPOTRANSPIRATION

The most common methods for estimating evapotranspiration are energy balance, aerodynamic, and eddy flux. These methods have been reviewed and discussed in detail by Eagleson (1970), Hanks et al. (1973), van Bavel (1966), Swinbank (1965b), Ward (1971), Horton (1973), and Rosenberg et al. (1968). Each method and some of its variants are briefly described.

### Energy Balance

The energy budget, which measures incoming and outgoing radiation, is one of the chief methods used for estimating evapotranspiration (Penman, 1963). The energy balance equation usually includes four components; net vertical flux of radiation (R<sub>n</sub>), sensible heat flux into and out of the ground (G), sensible heat flux into and out of the air (H), and latent heat flux into the air (LE). These components are related through energy balance by the equation:

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$$R_n \pm G \pm H \pm LE = 0$$

The components of photosynthesis (P) and energy of respiration (R) represent minor amounts of energy, and are usually omitted from the equation. Net vertical flux, sensible heat flux into the ground and latent heat flux into the air are relatively easy to measure. Therefore, latent heat flux and sensible heat flux into the air must be apportioned according to Bowen's ratio:

$$\beta = f \left( \frac{T_o - T_a}{e_o - e_a} \right)$$

Numerous empirical formulae have been developed for estimating evapotranspiration based on the energy balance method including formulae proposed by Bowen (1926), Penman (1948, 1963), Tanner (1966), Jensen (1966), and others (Penman, 1963). Each of these are of limited value and their use should be restricted to the area and conditions for which they were developed (Hounam, 1972).

The Bowen ratio is perhaps the simplest method of integrating the components of the energy balance equation (Lourence and Pruitt, 1971). But, it is only valid if H and E are measured at the same height and the transfer coefficients for heat and water vapor are identical (Swinbank, 1965b). Fritschen (1965, 1966) has used the Bowen ratio to successfully estimate evapotranspiration in the semi-arid southwest of the United States. However, a reasonable estimate of the 24-hour Bowen ratio must be developed to adequately estimate evapotranspiration in arid regions (Tanner, 1960).

Although Penman later recognized the ability of plants to regulate transpiration (Penman, 1963), his original formula was developed from rejection of the idea that transpiration is a vital process controlled by the plant. He regarded transpiration as something that cannot be avoided since it is a "passive" response of the plant to the environment. Therefore, the obvious measurement from which evapotranspiration could be estimated was the energy budget. He concluded that as long as conditions for potential transpiration are satisfied (water non-limiting) and the local air temperature is determined by the local energy budget, estimation of evapotranspiration by an empirical formula should be quite accurate. He also assumed that the transport of sensible heat into the atmosphere (H) is governed by temperature differences similar to the transport of water vapor caused by differences in vapor pressures. Abdel-Aziz et al. (1964) found that neither the Penman formula nor any modifications tested adequately accounted for advective energy. Therefore, under semi-arid conditions, the Penman formula is not a satisfactory method to estimate evapotranspiration (Table 1). Generally, however, the Penman formula has worked satisfactorily over a wide

range of climates. But, there is often a tendency to underestimate evapotranspiration because of variable wind speeds and surface roughness (greater than for short grass) (Tanner and Pelton, 1960).

In 1966, van Bavel proposed a formula in which he included transfer functions for sensible heat and water vapor. This formula eliminates the empiricism contained in the original Penman formula. It also incorporates an aerodynamically based wind function that is valid regardless of amounts of advection over any surface. This approach is good for estimating evapotranspiration from open water, irrigated alfalfa (*Medicago sativa*), and wet bare soil (van Bavel, 1966).

### Aerodynamic

The aerodynamic or wind profile method (King, 1966) for estimating evapotranspiration was first proposed by Thornthwaite and Holzman (1942) utilizing Dalton's mass transfer equations (Roberts, 1969). Dalton's equation demonstrates that evaporation is a product of a vapor pressure gradient existing between the evaporating surface (water) and the air above the surface as influenced by the wind. This requires the measurement of wind velocity at different heights from which evaporation can be estimated by use of the mass transfer equation. Blackwell and Tyldesley (1965) reported that the aerodynamic and energy balance methods are only suitable for arid zone situations provided the effects of buoyancy forces are taken into consideration.

### Eddy Fluctuation

This technique requires highly specialized instrumentation and data processing facilities to be useful in estimating evapotranspiration (Goddard and Pruitt, 1966). The instrumentation must have a short response time (of the order of 1 second) to account for all the fluctuation in atmospheric turbulence (Swinbank, 1965b). However, it is an effective method for estimating evapotranspiration in arid regions that encounter large temperature lapses (Blackwell and Tyldesley, 1965).

### Empirical Formulae

Several empirical formulae have been developed from which evapotranspiration can be calculated by utilizing measurements of air temperature (Criddle, 1966; Thornthwaite, 1948). Thornthwaite (1948) reported that it is difficult to determine the degree of wetness of an environment by the amount of precipitation that occurs. Therefore, he proposed a formula for estimating evapotranspiration from knowledge of the latitude and the average air temperatures. This approach has been useful in physiography, but it is inadequate where absolute values are important (Pelton et al., 1960).

### METHODS OF MEASURING EVAPOTRANSPIRATION

The most direct and least complicated method for measuring water loss through evapotranspiration is the water-budget method (van Hylckama, 1974). The water budget or water balance accounts for the difference in water applied to an area and subsequent water lost via evapotranspiration (Branson et al., 1972) by the equation:

$$P - O - U - ET + \Delta W = 0$$

The components comprising the water balance equation include precipitation (P), runoff (O), deep drainage (U), evapotranspiration (ET), and change in soil water storage ( $\Delta W$ ). This method involves soil moisture and watershed studies (Douglass, 1965) and the use of evapotranspirometers (van Hylckama, 1969; 1970; 1974), lysimeters (Pruitt and Angus, 1960; van Bavel and Reginato, 1965), or evaporation pans (Pruitt, 1966).

Lysimeters have been used to study percolation since 1688 but interest in evapotranspiration did not develop until the late 1800's (Harrold, 1966). Use of lysimetry to measure evapotranspiration has substantially increased since 1945.

Some of the earliest large lysimeters were constructed on the San Dimas Experimental Forest in 1937 (Patric, 1961). These lysimeters were designed to measure water that fell on, ran off, and seeped through the soil supporting various kinds of vegetation. Annual evapotranspiration from vegetation growing in these lysimeters is computed from the water balance equation.

Three kinds of lysimeters most commonly used today are weighing, non-weighing and floating. Weighing lysimeters have been constructed in Arizona (van Bavel and Reginato, 1965) and California (Pruitt and Angus, 1960) for measurement of evapotranspiration in those areas. Weighing lysimeters have been designed to

**Table 1. Comparison of evapotranspiration values obtained from lysimeters (ETL) with the Penman equation (ET pen), van Bavel combination formula (ETvb), Bowen ration (ETB), and aerodynamic method (ETA). (Data extracted *in toto* from Hanks et al., 1973).**

Date	ETL	D <sup>a</sup>	z <sub>o</sub> <sup>b</sup>	ETpen <sup>c</sup> X 0.485 Wm <sup>-2</sup>	ETvb	ETB	ETA	Rn-s <sup>d</sup>
6- 7	147	0.5	0.05	262	250	47	24	260
14	272	1.7	0.3	256	262	282	198	328
17	301	3.1	0.5	264	333	325	234	304
30	270	22	3.4	197	275	219	71	241
7- 1	415	24	3.7	312	472	304	144	352
2	343	26	4.0	264	482	342	102	268
3	422	27	4.3	331	606	489	121	375
4	292	30	4.6	198	359	179	90	224
5	408	31	4.8	307	531	372	121	353
6	313	32	5.1	237	394	283	166	276
8	284	34	5.4	253	380	295	95	304
9	441	35	5.5	292	467	346	127	304
10	475	36	5.7	344	600	441	115	350
11	460	36	5.8	337	645	374	191	342
12	396	38	6.0	275	603	358	81	265
13	428	38	6.0	345	603	414	178	356
14	499	39	6.1	339	763	386	138	320
19	433	42	6.6	324	504	299	47	333
20	402	43	6.7	336	856	192	395	321
23	253	44	7.0	306	390	257	32	330
8- 1	296	48	7.6	319	628	419	215	317
3	186	48	7.6	262	342	392	17	295
4	166	48	7.6	285	336	441	21	331
5	224	48	7.6	322	546	413	90	332
6	150	48	7.6	296	436	327	31	312
8	47	48	7.6	298	543	353	34	299
9	36	48	7.6	294	655	245	73	260
Average June 30 to July 20								
	389			293	534	331	136	311

<sup>a</sup>D = displacement depth in cm.

<sup>b</sup>z<sub>o</sub> = roughness length in cm.

<sup>c</sup>Rn-s = net radiation minus soil heat flow.

<sup>d</sup>Original data reported in Langleys per day; converted to watts per square meter.

accurately measure short-term (1 hour or less) evaporative flux (weight changes equivalent to  $2.54 \times 10^{-3}$  cm over a 6.1 m diameter surface area). Smaller weighing lysimeters can accurately measure evapotranspiration weighed to the nearest 20 g.

Non-weighing lysimeters are designed to determine evapotranspiration either from the change in the water level in the lysimeter after adjustments are made for precipitation or from change in soil water storage (Harrold, 1969). However, soil water storage must be measured without disturbing the natural soil structure (e.g., through the use of the neutron probe, tensiometers, psychrometers, etc.).

Floating lysimeters, similar in design to the weighing lysimeter except they operate on the principle of water displacement rather than actual weight, are quite sensitive ( $> \pm 5.08 \times 10^{-3}$  cm) and provide an excellent measurement of water loss via evapotranspiration (Pruitt and Angus, 1960). Measurements of evaporative flux can be determined hourly.

It has long been accepted that transpiration of "facultative phreatophytes" and evaporation from shallow pans of free water are highly correlated (Briggs and Shantz, 1916; 1917). However, the ratio of evapotranspiration/evaporation (ET/E) is dependent upon the type of pan or tank used to measure evaporation (Pruitt, 1966). Pruitt presented very convincing evidence that evapotranspiration of perennial ryegrass (*Lolium perenne*) was highly correlated with evaporation when measured with a U.S. Class A evaporation pan. Results of research conducted by others indicated there is also a high correlation of pan evaporation and evapotranspiration from green peas (*Pisum* sp.), early potatoes (*Solanum tuberosum*), raspberries (*Rubus* sp.), peaches (*Prunus persica*) with a cover crop of alfalfa, sugar beets (*Beta vulgaris*), red beans (*Phaseolus* sp.), ladino clover (*Trifolium repens* var. *giganteum*), soybeans (*Glycine max*), corn (*Zea mays*), grapes (*Vitis* sp.), and delicious apples (*Malus pumila*) (Pruitt, 1966). It is important that local pan environment be standardized throughout growing seasons to achieve reliable measurements of evapotranspiration.

#### EFFECTS OF SOILS ON EVAPOTRANSPIRATION

Soils have a significant effect upon the potential evaporation rate of any given area. The kind, color, and physical condition of the soil are particularly important in influencing the evaporation rates. Lull (1964) reported that water evaporates rapidly from compact soils. He also reported that evaporation from dark colored soils was greater than from light colored soils. Less water is lost through evapotranspiration as the friability of soil increases.

The water content of bare soils seems to be one of the most influential factors affecting the evapotranspiration

rate. It has repeatedly been shown that a thin layer of dry soil at the surface can stop or diminish evapotranspiration (Penman, 1941; Philip, 1958; Veihmeyer, 1964; van Hycklama, 1966a; and Ripple et al., 1972). Veihmeyer (1938) has also shown that upward movement of water from wet soil through dry soil is slight and the evaporation rate is negligible. However, evaporation from the soil surface will continue at a rapid rate as long as the soil surface is kept moist (Lull, 1964; Veihmeyer, 1964).

Although summer fallow has long been practiced in agriculture, it is now evident that this practice significantly increases the soil water storage. Average water use efficiency for fallow wheat was 80 percent greater than that for continuous wheat (Smika, 1970). Soil water storage was as much as 3 cm more in the fallow area than in the controlled area (Greb, 1974). New fallow techniques utilizing better fallow and weed control management have increased storage efficiency from 17 to 20 percent in the early 1900's to 35 to 41 percent in 1970 (Greb et al., 1974). Use of silicone or cetyl alcohol coating on soil particles creates a nearly perfect dust mulch at the soil surface and acts as a barrier to the evapotranspiration (Hillel, personal communication; Kijne, 1973; Rawitz and Hillel, 1973). This practice has the potential to make agriculture economically feasible in some semi-arid areas of the world.

The depth to which water is depleted from the soil through evaporation is about 10 cm for clay and about 20 cm for sands. However, if the surface soils are allowed to dry, the evaporation rate is substantially decreased. If the soils are saturated and in constant contact with a free water surface (e.g., water table), upward movement of water through the soil is continuous and quite rapid and evaporation rates are quite high. Veihmeyer (1964) found that if the water table was within 30.5 cm of the soil surface, evaporation is comparable with the transpirational loss for an irrigated crop. However, in unsaturated soils the evaporational water loss is only a very small portion of the total loss of the water from the soil.

Although potential evapotranspiration is governed primarily by meteorological conditions, actual evapotranspiration is influenced by the plant itself (Lemon et al., 1957) and by the abundance of water in the soil (Penman, 1963; Eagleman and Decker, 1965) as well as by meteorological factors. Eagleman and Decker found a negative linear relationship ( $r = -0.74$ ) between the soil water potential and the relative evapotranspiration rate. Actual transpiration of corn decreased with decreased soil water content and increasing potential transpiration (Denmead and Shaw, 1962; Pallas et al., 1962; Shimshi, 1963). Limiting soil water (7 percent by weight) determined the transpiration rates in *Eucalyptus camaldulensis*, *E. gomphocephala*, and *E. occidentalis* (Gindel, 1971). Veihmeyer and Hendrickson (1955a; 1955b) hypothesized that the rate of evapotranspiration remains near the maximum for any set of environmental conditions

until the level of soil moisture approaches permanent wilting. As the soil water content approaches the wilting point, the evapotranspiration rate falls rapidly with losses limited to evaporation from the soil surface. Denmead and Shaw (1962) and Yang and de Jong (1972) found that the relationship between evapotranspiration rate and soil water content varied with different demands from the environment. Evaporation demands directly influenced evapotranspiration until a critical soil water potential was attained (Cary, 1971; Haas and Dodd, 1972).

Water loss via transpiration in ponderosa pine (*Pinus ponderosa*), lodgepole pine (*P. contorta*), Douglas-fir (*Pseudotsuga menziesii*), grand fir (*Abies grandis*), and Engelman spruce (*Picea engelmannii*) seedlings decreased with decreasing soil water potential (Lopushinsky and Klock, 1974). The transpiration rate of all the species began to decline at a soil water potential of -1 to -2 bars, but the degree of reduction of transpiration rate differed with the species. At a soil water potential of -10 bars, the transpiration rate of the pines was only about 12 percent of their maximum rate, while the transpiration rate of firs was 27 percent to 37 percent of their maximum. Preliminary research conducted under the auspices of the U.S./IBP Desert Biome Project (Campbell and Harris, 1974) indicated that transpiration of sagebrush (*Artemisia tridentata*) decreased with decreasing soil water potential. Nkendirim and Haley (1973) found that evapotranspiration from "prairie grass" decreased with a decrease in soil water content. Soil moisture as low as 18 percent (by volume) supported actual evapotranspiration equivalent to the potential evapotranspiration. When the soil moisture fell below 11 percent (by volume), the grass became quiescent and water loss was directly from the soil surface.

It has generally been assumed that under semi-arid and arid conditions, transpiration is the predominant cause for the loss of water from soils (Veihmeyer, 1964; Harrold, 1969). However, Beardsell et al. (1973) found that transpiration of soybeans was closely correlated to water stress. At -0.4 bar soil water potential, the rate of transpiration became independent of the atmospheric conditions. Recently, it has been shown that transpirational water lost by mature honey mesquite (*Prosopis glandulosa*) is related to the soil water potential (Easter and Sosebee, 1975). The transpiration rate for trees growing under artificial irrigation ( $\Psi_{\text{soil}} = -1$  bar) was  $9.59 \times 10^{-5} \text{ g cm}^{-2} \text{ min}^{-1}$  compared to  $7.15 \times 10^{-5} \text{ g cm}^{-2} \text{ min}^{-1}$  for trees growing under natural environmental conditions ( $\Psi_{\text{soil}} < -11$  bars). On the contrary, Wendt et al. (1968) found no differences in transpiration rates of honey mesquite seedlings grown at soil suctions from 0.1 to 15 bars.

Pallas et al. (1962) reported that vegetation has the ability to regulate the amount of water lost via transpiration through stomatal closure. Transpiration rates of Kings fescue (*Hesperochloa kingii*), a species native to northern Utah, ceased in mid-afternoon during

the growing season, whereas the transpiration rates of smooth brome (*Bromus inermis*) and intermediate wheatgrass (*Agropyron intermedium*), species introduced to northern Utah, continued to increase (Brown, 1973). Since species adapted to particular environmental regimes respond to the environment in ways which would allow them the greatest chance of survival, perhaps more research concerning wildland species growing in their native habitats (especially in arid and semi-arid regions) will reveal that transpirational water loss is indeed regulated by the plants.

Van Hylekama (1963) found a distinct decline in the use of soil water by saltcedar (*Tamarix pentandra*) with increasing depths to groundwater. Similar relationships were found in greasewood (*Sarcobatus vermiculatus*) in which water use rates were a function of depth to groundwater (Harr and Price, 1972).

Soil salinity is a very important factor that one must consider in calculating evapotranspiration from soils. Van Hylekama (1966b) estimated that salinity of soil reduced water use by plants by 40 percent. As the soil salinity approaches the point where nothing germinates (58 mSeimans), there is essentially no water lost from the topsoil. Therefore, it is necessary to consider soil salinity when estimating evapotranspiration by particular phreatophytes such as saltcedar.

#### EFFECT OF VEGETATION ON EVAPOTRANSPIRATION

Plants most often have been relegated as "villains of the landscape" with respect to water use. "Insidious thieves steal more water every year in Texas than is used by all the towns, all the factories, all the farms, and all the people. They annually use almost five times as much water as is stored in all the reservoirs in the state" (Rechenhth and Smith, 1967).

Several factors must be considered when evaluating the effect of vegetation on evapotranspiration; kind of vegetation, phenological development, stand density, and innate transpiration characteristics. Many studies have been conducted in which forest cover has been altered to affect water yield (Hibbert, 1965). Removal of forest trees has invariably increased water yield from the controlled watersheds through decreased evapotranspiration as well as through increased streamflow (Hoover, 1945; Johnson and Kovner, 1954; Kovner, 1956; Hibbert, 1969; Hewlett and Helvey, 1970; Hornbeck et al., 1970; Rothacher, 1970; and Patric and Reinhart, 1971). Soil moisture in deforested soils remained near maximum storage capacity even during the growing season (Rothacher, 1970; Patric and Reinhart, 1971). Rothacher speculated that increased water yields are possible due to elimination of evaporation from interception. Hornbeck et al. found increased streamflow following elimination of transpiration and canopy interception losses by deforestation in New



England. Soil water storage under grass cover is greater than under shrub cover because interception of precipitation by shrubs is greater than by grasses (Corbett and Crouse, 1968). Interception losses may account for as much as 10 to 40 percent of the annual precipitation (Croft and Hoover, 1951).

The greatest increase in streamflow following deforestation usually occurs during the growing season. Groundwater storage was at a maximum on both a treated and untreated deciduous forest during late winter and early spring (Johnson and Kovner, 1954). Hornbeck et al. (1970) reported a 40 percent and 10 percent increase in streamflow during the first and second year, respectively, following treatment (cutting followed with herbicide application) of a deciduous forest. Most of the increase occurred during the growing season. Gifford and Shaw (1973) reported increased soil moisture storage on pinyon-juniper (*Pinus edulis*—*Juniperus osteosperma*) sites where the woody species had been removed and the debris was left in place. Removal of sand shinnery oak (*Quercus havardii*), grasses, and forbs significantly increased soil water storage in West Texas (R. D. Pettit, unpublished data). However, removal of either the sand shinnery oak or the herbaceous vegetation produced little increase in soil water storage annually when compared to removal of no vegetation.

The kind of vegetation is pertinent to evapotranspirational water lost from an area. It is generally conceded that evapotranspirational loss from grass is less than from a forest, and shrubs are intermediate. Metz and Douglass (1959) and Douglass (1965) have shown that grass depletes soil water less than trees and shrubs. Douglass reported annual grasses deplete water from shallower depths than trees. Most water depletion by grasses occurs during winter and spring. Invasion of forbs into an area depleted soil moisture to greater depths and for a longer period of time. After grasses matured, evapotranspirational water loss was negligible (Hibbert, 1969; Hibbert et al., 1974). Conversion of the San Dimas watersheds from brush (scrub oak chaparral) to grass significantly increased soil water storage during the year following brush control (Rowe and Reimann, 1961). The carry-over of soil water at the end of the drying season under a grass cover was twice as great as under a brush cover. Johnston and Doty (1972) found that soil moisture depletion under a grass cover was about half the amount depleted by aspen (*Populus tremuloides*) communities. Recently, B. E. Dahl (unpublished data) has found that during very hot summers, soil water depletion within mesquite stands is often less than in areas where mesquite has been controlled.

Previous research indicates that consumptive use by different kinds of plants is stratified according to soil depths and season of the year. Soil water depletion occurred at shallower depths (to 30 cm) in the spring and late fall when the grasses and forbs were actively growing, whereas, depletion of soil water at lower depths occurred

during the summer when sand shinnery oak was most actively growing (R. D. Pettit, unpublished data). Hibbert et al. (1974) found that chaparral shrubs depleted soil water to a greater depth than shallow-rooted grasses and forbs. Since the chaparral species are evergreen, evapotranspiration can occur any time during the year that environmental conditions (soil and climate) are favorable. Transpirational studies involving honey mesquite indicated that the most active root absorption occurs in the upper 60 cm of the soil (Easter and Sosebee, 1975). Recently, G. W. Thomas and R. E. Sosebee (unpublished data) found that foliage production and transpiration rates of honey mesquite was not affected when the taproot was severed at a depth of 70 to 75 cm (below the first group of lateral roots that occur at the 30 to 60 cm depth). Seemingly, honey mesquite does not depend on a deep root system for absorption of water, except possibly during extended droughts when the upper 60 cm of soil water content remains below the wilting point (Cable, 1973).

Patric (1961) found that initially evapotranspirational water loss from grass and pine (*Pinus coulteri*) was greater than from scrub oak (*Quercus dumosa*). However, by the end of the growing season, there was no difference in evapotranspirational loss between the woody species.

Kovner (1956) suggested that evapotranspiration opportunity is usually related to the extent of cover rather than to the characteristic of the vegetation. Reduction of density of a loblolly pine (*Pinus taeda*) stand reduced evapotranspiration (Douglass, 1960, 1965). He attributed evapotranspiration savings to changes in root distribution and in interception losses. Hoover (1952) reported that dense stands of trees will increase interception and transpirational loss of water, while thin stands will have less interception and transpiration but greater evaporation. Removal of dense stands of *Yucca* (5,000 plants/ha) increases soil water storage (Churchill et al., 1974). However, all *Yucca* must be removed to effectively increase soil water storage; partial elimination does not increase soil water storage. Similar results are reported for shrubs by Hibbert et al. (1974).

Robinson (1952) and Horton (1972) calculated the evapotranspirational water loss by saltcedar and reported an increase in evapotranspiration with increasing density in the stand. However, van Hylckama (1969, 1970) presented convincing evidence that water loss through evapotranspiration was not necessarily correlated to saltcedar density. Environmental conditions (air temperature, wind velocity, and relative humidity) within the interior of a stand of saltcedar are not conducive to high evapotranspirational loss.

Douglass (1965) found that stand height also influenced evapotranspiration of deciduous forests in the humid Southeastern USA. Evapotranspiration increased with increasing heights, possibly because of greater utilization of radiant energy and advective heat and increased air turbulence with increasing height.

Vegetation tends to reduce evapotranspiration by shading the soil and by reducing the wind velocity. However, absorption of water by the plants and interception of precipitation usually more than offset the effects of vegetation in retarding evaporation from the soil (Lull, 1964).

#### EFFECTS OF LANDUSE (GRAZING) ON EVAPOTRANSPIRATION

The literature is practically devoid of information concerning the effect of grazing on evapotranspiration. Lull (1964) reported that frequent grass cutting results in less water use but more water is absorbed from the surface layer of soil. On the contrary, B. E. Dahl (unpublished data) found that neither light, moderate, nor heavy grazing affected the amount of water required to produce a pound of forage during June and August in eastern Colorado.

Possibly, the greatest effects of grazing on evapotranspirational water loss is through compaction of the soil by the grazing animal.

#### SUMMARY AND CONCLUSIONS

Studies involving evapotranspiration have been conducted since about 1875, although the concept was not described until 1944. Since 1944, many methods and techniques have been proposed whereby evapotranspiration can be estimated or measured. Unfortunately, most of the studies have been conducted on irrigated, cultivated crops. Irrigated, cultivated crops tend to become "facultative phreatophytes," therefore, they do not respond to the environment in the same way as native species adapted to particular environmental regimes. It is becoming better recognized that native plants are well attuned to the environment to which they are adapted, therefore, evapotranspirational water loss is not as great as estimated by conventional methods.

Douglass (1965) pointed out shortcomings of all methods presently being used to evaluate evapotranspiration loss. Use of soil moisture data is limited by plot size, inadequate sampling depth and lack of replication. Lysimeter studies are limited by boundary effects, size and "oasis" and "clothesline" effects. Douglass suggested that the energy balance and mass transfer methods (aerodynamic and eddy flux) may be the most promising, but they have many instrumental and theoretical difficulties.

Hanks et al. (1973) demonstrated that none of the methods most commonly used adequately estimated evapotranspiration of oats (*Avena sativa*) in northern Utah. They found that the energy balance approach including the Bowen ratio most closely approximated actual evapotranspiration by lysimetry, but these values underestimated evapotranspiration by 17 percent. During the growing season in which Hanks et al. conducted their study, the soil water content was not limiting. They found

that actual evapotranspiration was 1.33 times greater than that estimated by the Penman equation, 0.73 times that estimated by the van Bavel combination method, and 2.86 times greater than that estimated by the aerodynamic equation.

Douglass (1965) indicated that one of the greatest single limitations to interpretation of results of past studies has been the failure to recognize the dynamic nature of the process itself. Although the plant, soil, and atmosphere are part of a single dynamic system which transfers water to the atmosphere, most research has failed to include all three factors when studying evapotranspiration. Unfortunately, most studies attempting to estimate evapotranspiration by one of the methods previously discussed have been conducted using irrigated crops rather than wildland species in their native habitats.

Consumptive use of water by dense stands of vegetation has been extrapolated from measurements made on individual trees. Convincing evidence now exists that indicate consumptive water use by stands of vegetation is not necessarily directly proportional to the density of the stand. Evapotranspiration from within dense stands of vegetation is often much less than that on the periphery of the stand. Therefore, actual water loss is not as great as predicted.

Also, the amount of water transpired by native species within their native habitats (especially in semi-arid and arid regions) seemingly is not as great as purported. Upon further investigation of xerophytic shrubs, it may be anticipated that water is chiefly absorbed in the shallow root zone rather than by the deeper root system. Water absorption by deep taproots may be important only during extended droughts when the surface soil water content remains below the permanent wilting point. It is apparent, however, that many species function as "facultative phreatophytes" when soil water is unlimited, thereby increasing evapotranspirational water loss.

Removal of shrubs from an ecosystem and replacing them with grass usually increases soil water storage. Therefore, it is quite possible that interception (especially by shrubs) accounts for a greater loss of water than has been attributed to it in the past.

Estimation of evapotranspiration by empirical formulae or calculation of evapotranspiration from measurements taken in "artificial" environments tend to under or over estimate actual evapotranspiration. Water loss from semi-arid and arid environments seems to occur by some means other than evapotranspiration.

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# Erosion and Runoff on Forest and Range Lands

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## INTRODUCTION

In all phases of planning land use and management, we are concerned with maintaining or improving site productivity and preventing or reducing downstream damage. Logging, road construction, grazing, surface mining, and recreation are the major uses affecting erosion and runoff on forest and range lands. Although some general principles apply to all of these uses with respect to runoff and erosion, each use is discussed separately in this paper because each has its particular problems and solutions. Fire, although not a use, is included in this paper because it is subject to management and greatly affects erosion and runoff.

## LOGGING

Destruction of vegetation and disturbance of the soil mantle caused by logging operations often reduces infiltration rates and storage capacity of the soil mantle. The result is increased overland flow and erosion from watershed slopes. Although the detachment and movement of soil on site is not necessarily synonymous with movement of soil into stream channels, unchecked soil erosion eventually leads to sediment production. Consequently, forest management activities that produce hydrologic conditions leading to overland flow and soil erosion usually have the potential for damaging streamflow quality by sedimentation.

Research at a number of locations in America has shown that streamflow from undisturbed forests is generally clear except during periods of high discharge resulting from a heavy rainfall or rapid snowmelt. Illustrative of this are turbidities of streamflow from long undisturbed forest watersheds on the Coweeta Experimental Forest in western North Carolina (Dils, 1957), the Fernow Experiment Forest in West Virginia (Reinhart et al., 1963), the Hubbard Brook Experimental Forest in New Hampshire (Lull and Reinhart, 1963), and the H. J.

Andrews Experimental Forest in western Oregon (Rothacher, 1970). During nonstorm periods, suspended sediments from undisturbed forest watersheds range from about 1 to 11 p/m. Under most storm conditions, they remain well under 11 p/m, the accepted standard for drinking water. In some instances, extreme storm conditions may produce turbidities of more than 100 p/m.

There has been increased recognition of the need to determine the effects of various forest treatments on water quality. This realization has led to a few studies of the effects timber cutting has on streamflow and water quality when cutting is disassociated from other disturbances that normally accompany logging. The first such study in this country was the now classic Wagon Wheel Gap Experiment in Colorado (Bates and Henry, 1928). More recent studies have been conducted on entire watersheds to evaluate the unconfounded effects of timber cutting on water quality. Although few in number, these studies (Hoover, 1944; Dils, 1957; Lieberman and Hoover, 1951; U.S. Forest Service, 1960) show that timber cutting with felled trees left in place results in increased streamflow but little, if any, acceleration of overland flow and soil erosion. In other words, except for increases in streamflow temperatures where timber is clearcut for substantial distances adjacent to stream channels and except for possible increases in bank erosion caused by higher streamflow peaks, timber cutting itself usually does not adversely affect water quality.

While numerous studies have determined the amount of soil disturbed by logging and some have attempted to measure sediment yields, few have been concerned with the direct effects, unconfounded by the effects of roads, of logging on water quality. Many studies have indicated the magnitude of soil disturbance caused by different methods of logging (Garrison and Rummell, 1951; Fowells and Schubert, 1951; Trimble and Weitzman, 1953; Steinbrenner and Gessel, 1955; Wooldridge, 1960; Haupt, 1960; Dyrness, 1965, 1967, 1972; DeByle and Packer, 1972). Collectively, these studies show that, compared to balloon logging and high-lead cable systems of logging, tractor logging disturbs more area, compacts soil on a larger percentage of the disturbed area, causes more intensive compaction of soil, results in greater reduction of soil permeability, and produces larger amounts of overland

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flow and soil erosion. Measurements of logging disturbance and even of soil eroded from logged areas are not necessarily measures of damage to streamflow quality. Such measurements, however, do indicate the potential damage to water quality, especially where skid trails concentrate water, intersect other skid trails, and encroach upon or drain directly into stream channels.

Other studies in the United States illustrate the reduction in or prevention of watershed damage that can be achieved by careful planning and execution of logging operations (Wilm and Dunford, 1948; Dils, 1957; Kidd, 1963; Reinhart et al., 1963; Haupt and Kidd, 1965; Rothacher, 1970). These studies show that stream turbidity caused by logging usually occurs primarily during the logging operation and decreases rapidly, often in the first year, after logging. They also show that watershed erosion and damage to water quality can be greatly reduced or even prevented by carefully locating skid trails or skid roads with gentle grades on sites that do not encroach upon stream channels and by providing effective drainage of skid trails and skid roads to eliminate concentrations of overland flow.

Logging has sometimes been responsible for causing landslides and erosion on steep slopes, especially in parts of the western United States. Road construction on unstable terrain is the primary cause of such landslides, with the hazards being the greatest during or following heavy rains. However, even in the absence of roads, the increase in soil water and reduction in root support of the soil mantle that follows timber cutting can greatly accelerate landslides and erosion on steep slopes. The problems of mass soil movement are most critical in the coastal mountainous areas of northern California, Oregon, Washington, and southeastern Alaska (Swanston, 1968, 1969, 1970; Swanston and Dyrness, 1973). They also are important, but to a lesser degree, in various mountainous areas of the interior West, a notable example being the mass slumping of granite-derived soil in the mountains of central Idaho as the result of soil mantle saturation during rain-on-snow flood events.

Considering the current state of technology for handling the mass stability problem, the most useful approach appears to be that of identifying hazardous sites and avoiding them. Present techniques for identifying problem areas can very likely be applied throughout the world; however, such application will require that the land manager have adequate knowledge of local site conditions and erosion processes. Most identification techniques involve on-site inspection and use of aerial photographs, including infrared, special geologic maps, and analysis of drill cores.

Some attempts have been made to stabilize disturbed areas, but techniques are difficult, expensive, and do not always work. It is better to avoid disturbance in the first place. Swanston (1971) recommends careful design of

forest roads to avoid placing them on potentially unstable slopes, careful choice of timber harvest equipment and methods, and development and use of new harvesting methods (balloon and helicopter logging) to minimize soil disturbance.

Logging activities can introduce stumps, logs, limbs, and smaller debris into streams, but few investigations have been conducted to determine the effects of such introduction. Logging debris in streams can degrade water quality by decreasing dissolved oxygen and by releasing organic solutes. Meehan et al. (1969) noted that the amount of large-size logging debris capable of creating log jams on two Alaskan streams increased by 23 and 62 percent, respectively, during 4 years of patch clearcutting. Similar debris in a nearby unlogged watershed increased only 7 percent during the same period. Lammel (1973) and Froehlich (1971) both found that even narrow buffer strips of unlogged forest along streams were extremely effective barriers for preventing debris accumulation in streams. The major problem with debris in streams is that it forms jams that release vast quantities of water, logs, rocks, and impounded sediment when they fail. This results in tearing of channel banks, exposing fresh surfaces to erosion, and scouring of stream channels. Chapman (1962) found that when logging debris was not removed from west coast streams after logging, the numbers of spawning salmon dropped 95 percent because of the migration barriers created.

## ROADS

Many actual observations and research records indicate that most sediment (to 90 percent) from forest land that reaches stream channels originates on roads. Chief sources are roads that disrupt or infringe upon natural stream channels. Roads that have steep gradients or lack adequate drainage facilities to prevent swift concentrated overland flow from their surfaces are nearly as bad. Such roads can produce thousands of tons of sediment per square mile per year, depending upon inherent soil erodibility, steepness of topography, and storm magnitude or snowmelt runoff.

Despite the almost universal use of roads for access into timber harvest areas, few measurements have been made of the unconfounded effects of roads on runoff and soil erosion. The small amount of information available about the effects of roads is enough, however, to emphasize the seriousness of the problem. Although this paper emphasizes the importance of timber harvest roads, these special-use roads are not the only ones that pose serious erosion problems. Major highways that traverse forest lands can be equally, if not more, destructive.

In a few places, research has successfully isolated the effects that the various road and watershed factors have on runoff, soil erosion, and sediment production from forest roads (Trimble and Sartz, 1957; Haupt, 1959a, b; Packer

and Christensen, 1964; Packer, 1967; Megahan and Kidd, 1972). This research shows that erosion of road surfaces is primarily influenced by road characteristics that can be controlled through proper design and construction and by watershed characteristics than cannot be altered readily. Furthermore, sediment transport downslope from logging roads is influenced mainly by controllable road design characteristics, by watershed characteristics that are alterable through management, and by the age of the road. Guides that define design, construction, and maintenance care needed to assure stable roads have been developed.

Analyses of mass slope failures on forest lands on the north Pacific coast and on the Idaho Batholith indicated that most failures were associated with roads. In every road-associated failure, the steepness of both natural ground slope and fill slope was an important factor contributing to failure. As a result of laboratory tests and stability analyses, it can be concluded that no man-made slopes exceeding approximately 35° should be constructed without special provisions to assure stability. Also, live roots and trees are important factors influencing the stability of natural and artificial slopes (Gonsior and Gardner, 1971).

During snowmelt and heavy rainstorms, free water moves laterally through the soil on some mountain slopes, especially on steep slopes with porous soils, such as those in the Idaho Batholith (Megahan, 1972). Roads intercepting subsurface flow zones can cause significant changes in hydrologic behavior by modifying the natural paths and velocities of water movement. The subsurface water flows out of the road cuts, intensifying erosion of the road itself; and being diverted and concentrated, causes downslope damage as well. Such damage can be avoided by careful road location and design.

### GRAZING

On range lands, as on many other lands, our foremost concern is the prevention of excessive rain-splash erosion, the first stage of deterioration. On healthy range, the top layer of soil is usually the most permeable, the most fertile, and often the most resistant to detachment. Loss of part of this layer reduces fertility and infiltration. The resulting downward trend in plant growth and increase in overland flow leads to the more advanced stages of accelerated erosion. When rills and gullies have been cut, it is difficult and expensive to restabilize the slope. The key, then, is to avoid excessive rain-splash sheet erosion by maintaining sufficient cover density. But, the old questions arise, how much sheet erosion must take place to be termed "excessive?" and how much cover is needed to be termed "sufficient?" The usual answer to the first question is "erosion should not exceed the rate of topsoil formation." This is not a very satisfactory answer, leaving the range manager with little to rely on but his own judgment and experience. The second question has been the subject of a good deal of research and, although there are no precise

answers, some guides for range managers have been developed. The tolerance of range lands to grazing is highly variable from site to site, from year to year, and throughout each season. Some sites can be grazed heavily without damage; others deteriorate if grazed at all. Most range lands fall between these extremes.

Grazing tends to increase runoff and erosion by reducing plant cover density and by compacting or detaching surface soils. Trampling by grazing animals may also increase runoff and erosion by redistributing the litter cover and enlarging the bare openings (Packer, 1953). On steeper slopes, trampling contributes directly to erosion by moving soil and litter downhill. The selective grazing by livestock may also affect runoff and erosion by changing species composition. More often than not, it seems that the plant species preferred by livestock are the ones most effective as soil stabilizers.

On desert ranges in Nevada, Blackburn and Skau (1974) found that the presence of vesicular soils in the bare spaces between plants increased erosion rates because of their instability and poor infiltration rates. These vesicular horizons tend to increase with the removal of herbaceous vegetation by grazing.

On desert range in western Colorado, Lusby (1970) studied the effects of grazing exclusion on four paired watersheds (5 to 43 hectares). Over the 10-year period reported, runoff from the ungrazed watersheds was about 30 percent less than from the grazed watersheds and sediment was about 45 percent less. Cover remained essentially unchanged on the ungrazed watersheds, but decreased on the grazed watersheds. It would appear that grazing exclusion halted the downward trend on this desert range but did not bring about improvement during the 10-year study. Turner (1971) attributed the lack of recovery of the ungrazed watersheds to inherently low site capability and to subnormal precipitation. Permanent exclusion of grazing on such watersheds should be considered, particularly if their sediment is causing such downstream damage as reservoir siltation.

At the other extreme, on chaparral watersheds in central Arizona, Rich and Reynolds (1963) reported that runoff and erosion were not measurably affected by grazing.

The determination of proper timing and of grazing intensity remains a difficult problem. Severe overgrazing is easily recognized, but the downward trend resulting from slight overgrazing may be almost imperceptible until it reaches a point where it is difficult to reverse. Variations in growing conditions from year to year complicate the management problem. Sites vary greatly in their ability to withstand the impact of grazing. Some of our productive sites could support more grazing if it were properly timed and managed. But many of our arid lands and some of our steeper slopes in more productive zones have little



tolerance for grazing. These probably should be grazed only during more productive years.

We need a tool similar to the Universal Soil Loss Equation to help us determine which range sites have low erosion potentials and can support more grazing and which range sites should be grazed less or not at all.

The Universal Soil Loss Equation was developed for agricultural land east of the Rocky Mountains in the United States (Wischmeier and Smith, 1960, 1965). This equation integrates a large amount of research data. The basic equation is:

$$A = R K L S C P \dots\dots\dots(1)$$

where A is the average soil loss per unit area, R is the rainfall factor, K is the soil erodibility factor, L is the slope length factor, S is the slope gradient factor, C is the cropping management factor, and P is the erosion control practice factor. Each of these factors consists of an equation, a nomograph, or tabulated values. Soil loss is calculated as the product of the six factors. This equation allows each factor to be studied and evaluated somewhat independently of the others.

Research on each factor is still in progress to extend and refine this equation. It is being extended to steeper slopes, irregular slopes, construction sites, and undisturbed areas. Papers reporting findings of these efforts appear from time to time in such journals as the Transactions of the American Society of Agricultural Engineers. An equation of this form might well be adapted to express sheet erosion on western wildlands, particularly on range. Some attempts to develop such an equation are being made. For example, Tew (1973) has prepared a nomogram for estimating soil erosion losses from Utah watersheds, based in part on Wischmeier's equation and in part on other published information.

This type of development should be continued, incorporating all applicable data, published and unpublished, into an equation for western range. The equation could be written as follows:

$$\begin{aligned} \text{Log (Erosion)} = & f_1 \text{ (Rain)} + f_2 \text{ (Cover)} + f_3 \text{ (Slope)} \\ & + f_4 \text{ (Soil)} + \Sigma \text{ (Interactions)} \dots\dots\dots(2) \end{aligned}$$

This equation is essentially a logarithmic version of Wischmeier's Universal Soil Loss Equation and is compatible with it, in that any information contained in Wischmeier's equation that is applicable can easily be incorporated into the logarithmic equation.

The rain component includes intensity-duration probabilities; erosional effects of individual storms of known intensity-duration on known combinations of cover, slope, and soil; and integrated effects over a period of years on

characterized sites. The rain functions developed for the Universal Soil Loss Equation may not be applicable to western conditions because rainstorm characteristics in the West are different from those in the East.

Marston (1952) reported on the effects of various natural rainstorms on runoff and erosion from the Parrish Plots on the Davis County Experimental Watersheds in northern Utah. The plots are situated on uniform slopes and have a wide range of variation in cover characteristics. The data he presented for the years 1936-49, plus the data collected on these plots since 1949, should be very useful in the development of the rain function.

Packer (1963) in his study of erosion on the Gallatin elk winter range in Montana included the effects of 5-minute rainfall intensity on soil eroded from his runoff plots. Both Marston and Packer related erosion to maximum 5-minute intensity. The rain function in Wischmeier's equation is based on total storm depth and maximum 30-minute intensity. The rain function for western range should probably include 5- or 10-minute maximum intensity to get a better fit for western conditions.

On western range land, cover is obviously the factor to emphasize because of its dominant influence on sheet erosion and its sensitivity to land use. The most important function of vegetation, both living and dead, is the breaking of raindrop impact, which is the prime cause of soil detachment and usually the principal mode of soil transport. On the relatively gentle slopes of most range lands, the velocity of overland flow is rarely great enough to detach an appreciable amount of soil, unless the range has deteriorated to the point where rill and gully erosion occur. Vegetative cover further restrains erosion by impeding overland flow and by intercepting rain splash and the soil particles it carries. Cover also reduces erosion through its effects on the soil: supplying organic matter, creating root channels, enhancing habitat for soil fauna, and reducing temperature extremes and evaporation at the soil surface. These influences usually favor stability and infiltration.

Research has indicated that around 65 to 70 percent ground cover is usually needed for effective control of storm runoff and erosion (Packer, 1951; Marston, 1952). However, variations in rainfall, slope, and soil characteristics affect the amount of cover needed to hold soil loss to a specified level.

The slope function includes slope gradient, slope length, and slope shape. In the Universal Soil Loss Equation, the slope gradient factor is a parabolic equation, in which the effect of slope gradient increases as the gradient increases; and the effect of slope length is proportional to the square root of the length. Until recently, the Universal Soil Loss Equation has applied only to uniform slopes, but Foster and Wischmeier (1973) have developed a method to extend it to irregular slopes.

The effect of slope gradient on sheet erosion on western range land is illustrated in Figure 1. This graph is based on a multiple regression equation derived from data collected on plots at seven diverse high-elevation range sites in Utah, Idaho, and Montana (Meeuwig, 1971). Simulated rain was applied to these plots for 30 minutes at a constant intensity of 127 mm/h, and the resultant runoff and erosion were measured.

The regression equation follows the form of Equation (2) having cover, slope, soil functions, and an interaction term but no rain function because the simulated rain was the same on all plots. The interaction term involved slope gradient and cover. A reasonably good fit of the data can be obtained without this term, but it improved the fit enough to justify its inclusion.

This graph shows the combined effects of plant and litter cover (as measured by first strikes of a point analyzer) and slope gradient. The soil properties in the regression equation are fixed at their averages of 30 percent sand, 24 percent clay, and 8 percent organic matter. When cover is complete or nearly so, slope gradient is of little consequence. But slope gradient becomes increasingly important as cover is reduced. At less than 50 percent cover, erosion rates double for each 10 percent increase in slope gradient. The amount of cover needed to hold erosion within a specified limit varies widely with slope gradient. For example, if the limit is set at 100 g/m<sup>2</sup>, only 43 percent cover is needed on a 5 percent slope, but 82 percent cover is needed on a 35 percent slope. These relations are shown more clearly in Figure 2, based on a rearrangement of the same regression equation. If the

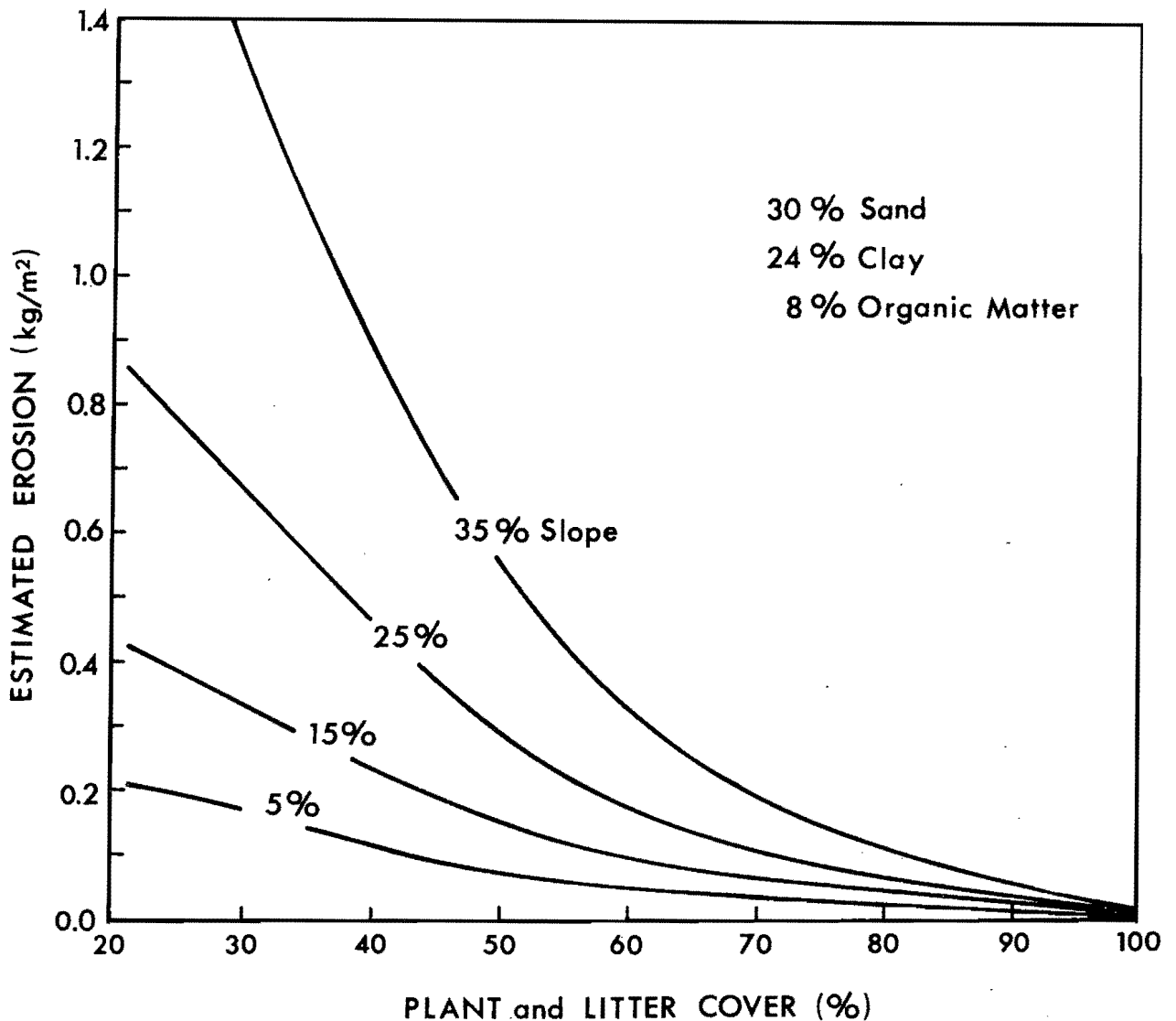


Figure 1. Erosion calculated as a function of slope gradient and percentage of the soil surface protected by plants and litter.

limit is set at  $50 \text{ g/m}^2$ , 61 percent cover is needed on a 5 percent slope as opposed to 91 percent cover needed on a 35 percent slope.

The soil component of this equation indicates that variations in soil can result in estimated erosion varying from less than half to more than twice the average values at any fixed combination of cover and slope (Figure 3). This variation is much less than that associated with cover or slope gradient but is still important. One of the most interesting results of this study is the interaction between soil texture and organic matter content. In fine-textured soils, erosion was found to be inversely related to organic matter content, a relation no one would question. But in sandy soils, especially those with less than 10 percent clay, erosion tends to increase with increasing organic matter content.

This seemingly anomalous relation is probably due to water repellency which has been found most commonly in sandy soils and is related to organic matter. Water repellency increases both detachability and transportability of sand. Dry sand is not cohesive, but moist sand is held weakly by water surface tension. If the sand particles remain dry during a rainstorm, they are easily moved by raindrop impact and overland flow. The water-repellent particles float on top of the overland flow. Water repellency tends to decrease infiltration rates, making more overland flow available for soil transport.

In other studies, erosion rates were affected by bulk density (Packer, 1963; Meeuwig, 1965; Yamamoto and Anderson, 1973). This is due mainly to its effect on infiltration rates and overland flow. Although overland flow is not very effective as a soil-detaching agent unless

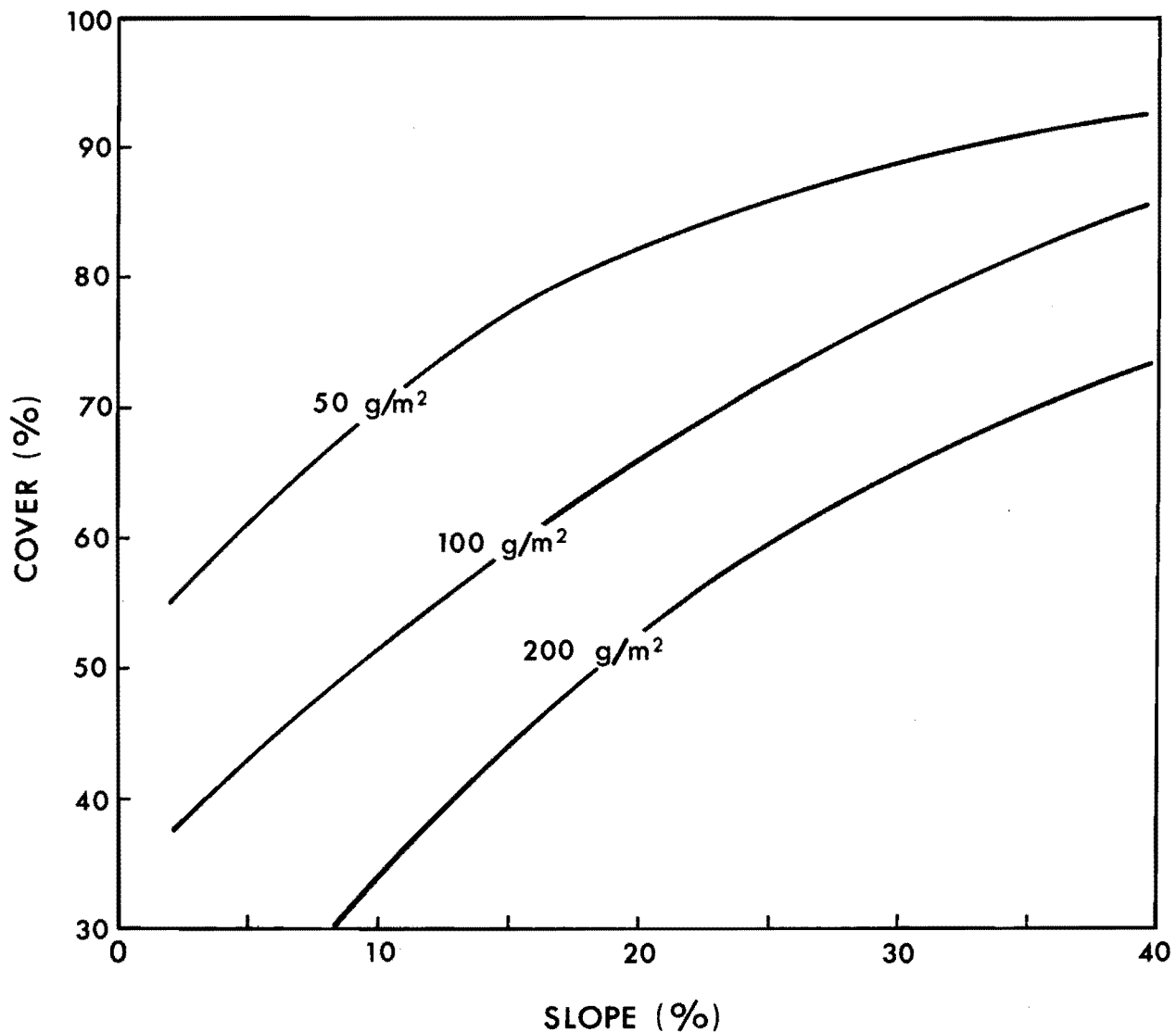


Figure 2. Effects of slope gradient on the percentage of plant and litter cover required to limit soil loss to 50, 100, or 200 grams per square meter under the impact of a 30-minute simulated rainstorm at a constant intensity of 2.1 mm/min.

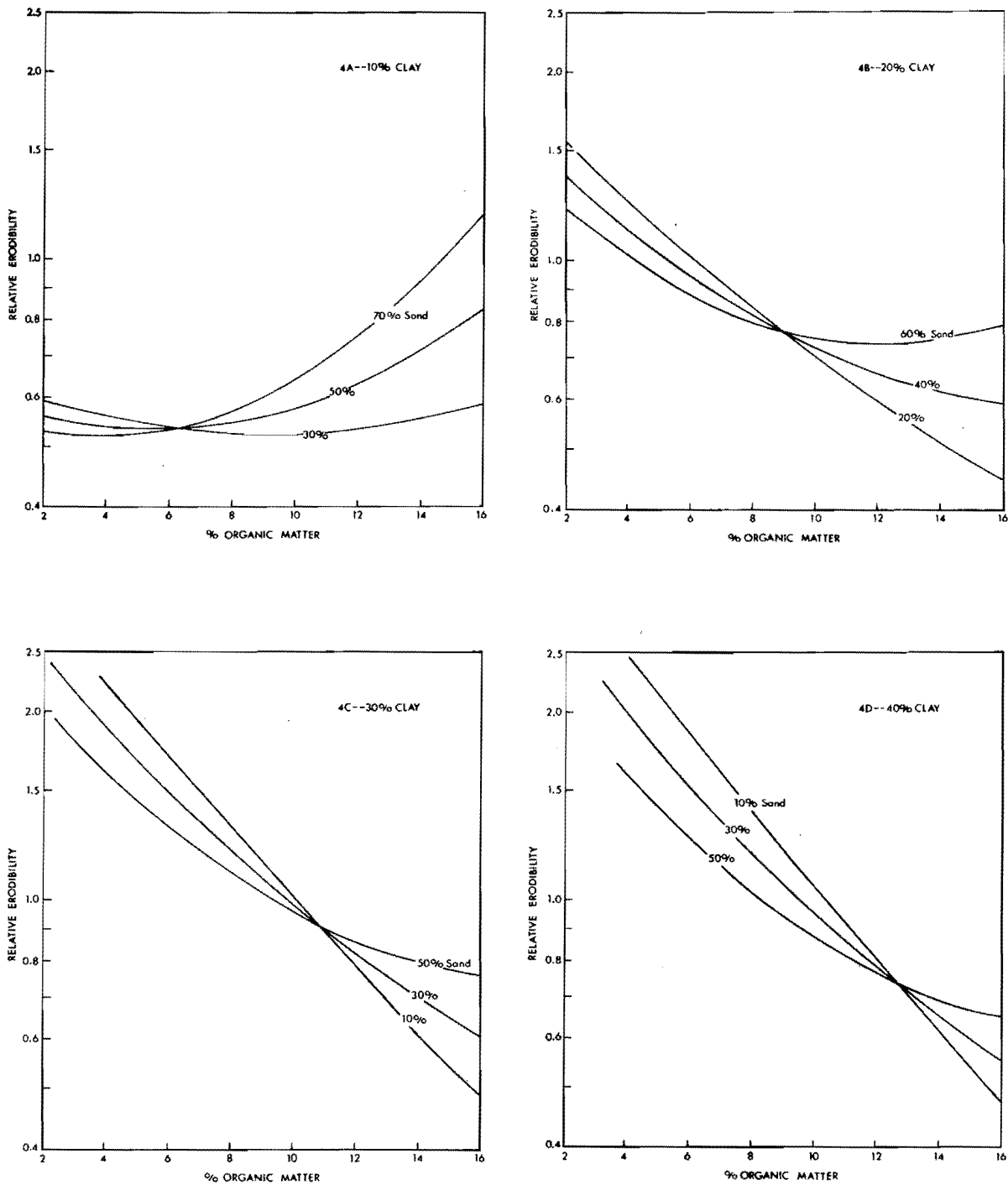


Figure 3. Relative erodibility as influenced by variations in sand, clay, and organic matter content of the surface inch of soil. Relative erodibility is the ratio of calculated erosion corrected for sand, clay, and organic matter to calculated erosion at average sand, clay, and organic matter.

concentrated in rills or gullies, the presence of overland flow increases the effectiveness of raindrops as detaching agents. If the soil surface is saturated and covered with a film of water, the raindrops striking it tend to rebound and to dislodge and transport soil particles. If the soil is only moist, the raindrops tend to penetrate the soil, dissipating at least part of their kinetic energy as frictional losses.

The relations between soil aggregation characteristics and erodibility have been studied for many years, and a number of ways of measuring and expressing aggregation as an index of erodibility have been devised. Middleton's (1930) dispersion ratio, van Bavel's (1949) mean weight diameter, Anderson's (1954) surface-aggregation ratio and several simpler expressions of aggregation have been significant variables in numerous studies of erosion and sedimentation.

Wischmeier et al. (1971) have published a nomograph for the soil erodibility factor *K* of the Universal Soil Loss Equation. The nomograph uses five soil parameters: (1) percent silt plus very fine sand (2 to 100 microns), (2) percent sand (100 to 2000 microns), (3) percent organic matter content, (4) soil structure on a scale of 1 to 4, and (5) permeability on a scale of 1 to 6. The authors state that the nomograph is applicable to farmland, construction sites, and other disturbed areas throughout the United States. Its adaptability to range and other wildlands should be tested.

An equation for erosion on wildlands would probably be limited to small uniform areas. If runoff is concentrated in channels, even as small as rills, the erosion process becomes too complex to handle with a general equation. Some form of modeling would be required.

A study by Branson and Owen (1970) provides a good illustration. Runoff and erosion from 17 watersheds in western Colorado were measured for 15 years. Mean annual runoff was closely correlated with percent bare soil, but the correlation between sediment yield and bare soil was not significant. Instead, they found that sediment yield was significantly correlated with angle of junction, relief ratio, and watershed area. The erosional processes taking place in the channels obscured the effects of vegetation on erosion on the side slopes.

## SURFACE MINING

Surface mining severely disturbs watersheds. All of the original vegetation and, in most cases, the original soil are completely covered with sterile spoils, toxic spoils, or both. Thus, an area of unprotected bare soil is created. It is only logical to expect that the basic hydrologic relations operating within a surface-mined watershed will be disturbed accordingly. Disturbance is not confined to the surface, however; the underlying bedrock is completely shattered down to the mineral bed in the mines and the materials from the various overburden strata are generally

quite thoroughly mixed. In some operations, the topography of watersheds can be drastically altered. Drainage divides may be shifted, stream channels rerouted, and surface gradients steepened or flattened. The extreme nature of these disturbances most certainly influences the basic hydrologic relationship. So far, little is known of these influences, especially in the western United States where little surface mining has been done until recently. The relatively small amount of research to determine the hydrologic influences of surface mining indicates that removal of vegetative cover and exposure of extensive bare soil areas increase surface runoff, at least temporarily. On the other hand, the large spoil piles resulting from surface mining absorb large volumes of water with the net effect of reducing streamflow from a watershed. Conclusions from such research (Coleman, 1951; Merz and Finn, 1951; Collier, 1964) indicate that while the effects of surface mining on surface runoff are highly variable from area to area, stormflows from surface-mined watersheds tend to be slightly higher than stormflows from similar undisturbed watersheds.

In a number of instances, the flow of small streams has changed from intermittent to continuous after surface mining. Again, however, few specific data are available (Medvic, 1965). It is entirely possible that watersheds containing mined areas have greater groundwater storage capacities and thus support higher base flows.

Loose soil materials, such as those recently disturbed by mining, are usually very susceptible to erosion. This is especially true when, as in the case of spoil dumps, the material is stacked in high piles having steep slopes. One of the primary sources of sediment in surface-mined watersheds is mass slumping where the fill portion of a mine dump breaks away and slides down the slope. Such slides result from highly excessive quantities of spoil material on steep slopes, from burying vegetation under the spoil dumps, from saturation of the spoil material, and from water seepage at the interface between the spoil dump and the original soil surface. The quantities of sediment originating from slides have never been measured, but over large areas of the eastern coal fields (Plass, 1967) and over mountainous areas of the West, slides are estimated to occupy from 5 to 10 percent of the total area disturbed by mining.

Haul roads in mined watersheds are another important sediment source. Surface-mine road systems are usually designed to move the mined material to storage, shipping, or processing points as directly as possible. Accordingly, where surface mining occurs in mountainous terrain, road gradients are often steep, drainage is sometimes poor or nonexistent, and road layouts frequently ignore design criteria. Consequently, erosion from cuts, fills, and bed surfaces is common. This is especially true after mining has been completed and haul roads have been abandoned. Weigle (1965) found that annual erosion from eight abandoned coal haul roads

ranged from 220 to 830 cubic yards per acre of road surface.

Probably the most important erosion source, excluding slides, is gully erosion that develops as a result of drainage outlets along the rims of terraced spoil dumps. Erosion from these gullies on steep slopes contributes large quantities of sediment to streams.

Large volumes of overburden rock material are shattered and exposed to the atmosphere during surface mining. These exposed materials weather rapidly. In some instances, as in the eastern coal fields and the heavy metals mining districts of the mountainous West, such weathering oxidizes and hydrolizes metal sulfides into acid solutions of heavy metals, some of which are toxic. In other instances, such as in the western coal fields, overburden materials are frequently highly saline, containing toxic concentrations of sodium attached to clays. Water running over or percolating through either acid or saline spoil dumps carries acid or saline salts into streams. Frequently, surface mines have been operated in conjunction with deep mines, thereby introducing the additional problem of acid or saline waterflow from underground mine portals. Regardless of the source, where acid, dissolved heavy metals, or saline salts from mining reach stream channels, they quickly deteriorate and almost completely debilitate the chemical and physical quality of streamflow. Reclamation of a stream damaged by surface mining requires termination of physical and chemical pollution from mine spoils and portals, removal of dead trees and brush accumulated as debris in the stream channels, and removal of toxic sediments from the stream by flushing or dredging, preferably the latter.

Erosion and chemical pollution from mine spoil dumps can be greatly reduced or eliminated by regrading the spoils after mining to gentle slopes, by burying toxic spoil materials during mining or construction of spoil dumps, by removing original topsoil before mining and replacing it when mining has been completed, and by revegetating mined areas as quickly as possible. In time, most spoil dumps can be restored to a condition equal to or better than the original land. Since restoration objectives will vary, the kind and degree of restoration will also likely vary (Packer, 1974).

### RECREATIONAL USE

Since World War II, especially since about 1960, an increasing and increasingly affluent population of Americans is finding more leisure time for recreation. Much of this recreational time is being spent in pursuing outdoor activities, many of which occur on our forest and range watersheds. Increasing recreational use has brought with it increasing impacts on vegetation, soil, and water. Runoff and soil erosion at and near points of recreational interest in many of our National Parks have increased as a result of soil compaction caused by trampling attending increasing

visitor use (Dotzenko et al., 1967). Similar impacts and effects are being experienced in a high percentage of forest campgrounds, especially those near high-population centers (LePage, 1967). Even in our wilderness areas, increasing recreational use from backpackers and trail riders is causing measurable deterioration of vegetation and soil, accompanied by increased runoff and erosion on choice camping sites near lakes and meadows where packhorses graze (Harvey et al., 1972).

During the last 20 years, the use of four-wheel drive vehicles, motorbikes, all-terrain vehicles, and snowmobiles has increased many times. The off-road use of four-wheel drive vehicles and motorbikes cross-country has created some appalling situations with respect to soil disturbance and concomitant runoff and erosion on steep mountainous terrain. If such damage to resources is to be controlled, restrictions concerning where and when these types of vehicles can travel should be published and enforced. Areas suitable for such use should be identified and reserved for that purpose. Similar problems exist in connection with all-terrain vehicles, but certainly not to the extent that they do with four-wheel drive vehicles and motorbikes (McCool and Roggenbuck, 1974). The authors know of no real runoff and erosion problems created by snowmobiles; however, there are reports that repeated heavy snowmobile traffic over the same trails can so compact the snow that its melting extends longer into the spring, occurs at a faster rate, and concentrates erosion-producing runoff down trails.

In recent years, there has been a remarkable increase in the number of skiers visiting the Nation's winter playgrounds. This has resulted in development of a large number of ski areas and facilities, most of which are located on forest land. Accordingly, some clearing of timber has been necessary on many areas in order to install and maintain ski lifts and develop ski runs. Unfortunately, such clearing has frequently been done with heavy equipment in such a way that not only timber but understory vegetation and the top few inches of the soil mantle have been removed. Baring of the soil mantle on steep slopes in areas of high precipitation has resulted in some conspicuous examples of concentrated surface runoff and gully erosion. Methods of correcting and preventing such damage are available and should be included as an element in the approved plans for development of such facilities (Klock, 1973).

Another form of recreation, "miniurbanization," is having a profound and usually adverse effect on some of our mountain watersheds. Miniurbanization is the activity involved in building of second homes and commercial lodging and eating facilities for recreational use, usually in mountainous watersheds within easy commuting distance of large population centers. Such urbanization can involve a number of acres of rooftops, walks, roads, and parking lots. Without control, all of these contribute concentrated surface runoff capable of causing soil erosion and damage

to streamflow quality in these watersheds. An even more serious problem in some of these miniurbanized watersheds is pollution of water supplies, a result of failure to plan and construct suitable sewage disposal systems.

### FIRE

Fire has been a major factor in the ecology of forests and grasslands in North America. In many places throughout the country, under natural conditions, large and profitable forests have developed following fire. Ponderosa pine, white pine, lodgepole pine, larch, and Douglas-fir are all seral types, largely perpetuated by wildfire. The role played by fires in regeneration of these forests is principally that of opening up the forest and creating a mineral soil seedbed. Where these forests are protected from wildfire but are opened up by timber harvesting, prescribed fire is one of the principal means for site preparation. Prescribed fire can rid areas of logging slash and other debris, eliminate competition, and create mineral soil seedbeds. Controlled fire can be used in combination with mechanical treatment to burn debris and windrows or piles, or it can be used to broadcast burn the whole surface. The main advantages of prescribed fire as a forest tool are its low cost and its suitability for use on steep slopes where mechanized equipment cannot be operated. Its major disadvantages are its potential wildfire hazard, its probable contribution to air pollution, and its possible deleterious effects to the hydrologic and stability behavior of the land.

Fires in grasslands can hardly be prevented from burning all the ground cover. Here, runoff and erosion consequences depend upon the kind of grass vegetation that is burned and the roughness of the terrain. Forest fires are much more variable, both in the way they burn and in the effects they exert upon the vegetation. Most conifers are ordinarily killed by fires hot enough to destroy most of their crowns. On the other hand, many hardwoods are not killed by fire, but quickly develop a new forest stand by sprouting from root crowns or suckering from roots.

Brushland fires are also variable as to the type of burn and the vegetation consequences. Where brush grows dense and low, crown fires are inevitable and the entire mass of vegetation burns. Where brush grows tall or in open stands, it is not entirely consumed. In effect, brushland fires exhibit characteristics of both grassland and forest fires, depending upon the weather during the fire and the structure of the vegetation.

The burning of any soil surface by fire results in increased release of water in the form of surface or overland flow. Such flow is undesirable from a water-yield standpoint. It can produce floods, waste water, lower water quality, impair the usability of water, and reduce subsurface flow proportionately. While fire studies show varying degrees of hydrologic effects, nearly every one of

them has shown that burning is followed by increased surface runoff and erosion (Megahan and Molitor, 1975). They further show that such increases result from the adverse effects that fire has on infiltration and storage characteristics of the vegetation-soil complex, especially where multiple burns occur within a few years. In a number of instances, floods and sediment from wildfire-burned forest lands have been observed to reach devastating proportions. One example of flooding following wildfires recurs periodically in southern California where intensive burning of chaparral-covered mountains is followed frequently by mudflows and floods of devastating magnitude that impinge upon highly urbanized areas.

The adverse hydrological and soil stability effects of controlled fire prescribed for land management purposes rarely assume such spectacular proportions. For example, prescribed broadcast burning of Douglas-fir logging residue on clearcuts in the Pacific Northwest leaves approximately 47 percent of the area unburned, 46 percent lightly burned, and 5 percent severely burned (Tarrant, 1956; Dyrness and Youngberg, 1957). This suggests that the prescribed use of fire on forests does not have to be highly destructive to the soil mantle.

Results from recent research on logged and burned larch—Douglas-fir sites in Montana show that the effects of prescribed burning on soil and vegetation can impair runoff and soil erosion control, both from snowmelt and from rainstorms. However, this impairment of watershed protection conditions and attendant increases in runoff and erosion are only temporary; having returned to the prelogging and preburning state within 4 years (DeByle and Packer, 1972). The small increase in plant nutrient losses, which occurred in the sediment and overland flow during the denuded period, represented only a small fraction of the available nutrients of these sites.

Research also shows that prescribed burning usually decreases soil acidity. Light burns normally increase soil nitrogen; but severe burns, such as those that can occur where residue is windrowed or piled, can decrease soil nitrogen by destroying organic matter. Prescribed burning also usually increases the amount of available phosphorus, magnesium, calcium, and potassium. The extent to which these mineral nutrients enhance soil fertility and benefit the new forest depends upon how quickly young seedlings are established in relation to the rate of leaching in the soil profile.

The development of water-repellent substances in soils has been attributed, in part at least, to the production during fires of a series of pyrolytic substances obtained from the original organic material in the soil and from the comprising vegetation. More information is needed concerning the amounts of water-repellent substances that can be expected to move during wildfires and prescribed burning. The susceptibility of different soils to water

repellency under fire conditions, and the technology for ameliorating water repellency need further investigation.

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# Runoff and Erosion

Walter C. Boughton\*

## INTRODUCTION

There have been several extensive reviews and reports in recent years on how range and forest management affect runoff and erosion. Boughton (1970) reviewed over 1000 reports and publications, and surveyed problems of catchment management in Australia. Pereira (1973) summarized the information available throughout the world in the early 1970's to guide decisions on policy for land use management in watersheds. Other reports by the Food and Agriculture Organization of the United Nations (1973) and the International Hydrological Decade Working Group on the Influence of Man on the Hydrological Cycle (1972) give broad scope coverage of the topic. Reference is made in these reports to many of the fine bibliographies, proceedings of conferences, and collations of information which were prepared in earlier years.

The subjects of runoff and erosion are both wide in scope. In order to cover runoff with clarity in the limit of this paper, the subjects of water yield and floods are discussed separately. The quantity of water yield from a catchment which is available for practical use is determined by sustained periods of low flow in protracted droughts; while at the other extreme, floods occur in very short periods of very high rainfall and runoff. From the viewpoint of management of watersheds, it is simplest to consider these as separate issues under the headings: Water Yield and Floods.

## WATER YIELD OF CATCHMENTS

In Australia, estimating the water yield of a catchment is usually associated with estimating the water supply available from a storage or by diversion, pumping, etc. There are two areas of interest—establishing a rainfall-runoff relationship in order to estimate runoff from rainfall; and defining the effects of land use and land management practices on the volume of runoff.

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## Rainfall-Runoff Relationships

Rainfall-runoff studies vary depending upon the data available for analysis and the size of catchment concerned. On small catchments, for design of farm dams and soil conservation works, there are rarely if ever any records of streamflow. In practice, a number of relatively crude techniques are used to assess average annual runoff from average annual rainfall. In 1967, the Department of National Development produced a map of average annual runoff in inches over the continent at a scale of 1:6,000,000 (Australia, 1967). In the past decade, the method developed by the Soil Conservation Service of the U.S. Department of Agriculture for estimating runoff from daily rainfalls has been used increasingly in practice to estimate the temporal pattern of runoff.

On medium to large catchments without records of runoff, the most common practice is to establish a rainfall-runoff relationship on the nearest available gaged catchment, and use this relationship with rainfall records in the catchment to be studied to estimate its runoff pattern.

Where some overlapping records of runoff and rainfall are available, modern techniques for computer simulation of catchment water balance enable runoff to be estimated from rainfall with a high degree of accuracy. I leave it to Professor Chapman to review Australian work in this field (see also Pattison and McMahon, 1973).

A major study of water yield has been funded by the Australian Water Resources Council in recent years (Snowy Mountains Engineering Corp., 1971). In the period 1969-1973, rainfall and runoff data from all small (less than 250 km<sup>2</sup> area) gaged catchments in Australia were collated and analyzed for yield and flood flows. Two methods were used to study the rainfall-runoff relationship from the viewpoint of yield. These were the USDA Soil Conservation Service method; and a daily water balance catchment model developed in Australia for small catchments (Boughton, 1965). The main objective of establishing relationships which might be used on ungaged catchments was not achieved; however the study was a major step forward in showing the amount of small catchment data

available in Australia and the state-of-the-art of analysis for yield.

Also, there is a continuing program of instrumenting and studying a total of 93 catchments throughout Australia with areas 25 to 250 km<sup>2</sup>, termed "Representative Basins" (Australian Water Resources Council, 1969a). These have been selected on the basis of climate, relief, and land form to sample the major variations in catchment characteristics throughout the country. This deliberate selection ensures that hydrological data will be collected from at least one catchment in each major climatic-geomorphic zone that otherwise may not have been included in the general water resources stream gaging network of more than 3000 stations.

#### Land Use and Water Yield

Most experimental catchments in Australia, whether operated by water supply authorities, soil conservators, foresters, agriculturalists or others, are used for the study of how land use effects water yield. The main problems being studied are: (1) the effects of clearing; (2) change in tree species; and (3) soil conservation works.

One of the major changes that has occurred in Australia during the period of European settlement is that large areas of native bush have been cleared for conversion to pasture or crop. Several changes appear to have occurred. Where deep rooting trees have been replaced by shallow rooting grasses, an increase in the total amount of runoff from the catchment or in the amount of groundwater recharge usually results. In Australia, the effects of clearing show up as an increase in groundwater recharge more often than as an increase in the amount of surface runoff.

In South Australia, Holmes and Colville (1968) have described the different rates of groundwater recharge between forest and grassland cover in the Cambier Plain. Vast areas of introduced pine plantation have replaced open grassland in this limestone country where surface runoff is very small. A rapid increase in groundwater use in recent years gives importance to the differences in annual recharge. Beneath the grasslands, there is an average through drainage of about 147 mm per annum (Allison, 1975) to recharge groundwater, whereas there is no through drainage beneath the pine forests. The present portion of the total area covered by pine forest is small, but the amount of available groundwater resource could be affected if the area was significantly increased.

In the 350-650 mm rainfall areas of Western Australia, South Australia and Victoria, the change from trees to grasses has resulted in the raising of saline groundwaters at the foot of slopes and in the bottom of valleys with subsequent salting of large areas of ground as water evaporates and salt is accumulated at the surface. It is

estimated that the areas affected are about 160,000 ha in Western Australia, 12,000 ha in South Australia, and 4,000 ha in Victoria.

Australia is well endowed with hardwood forest but is naturally deficient in softwoods. There is a current program of accelerated planting by forestry authorities to increase the area of coniferous plantation from an estimated 260,000 ha in 1964 to 800,000 ha by the year 2000. Much of the area planted will be in the better rainfall areas which form the main water supply catchments along the east coast of Australia. There are catchment experiments in both New South Wales and Victoria to study the hydrologic effects of change from native eucalypt to exotic pine species, and some results are available from the N.S.W. study. An early analysis by Bell and Gatenby (1969) of data from eleven catchments, ranging in size from 4 to 300 ha, showed no discernible difference in water yield between the species; however, a more recent report by Smith, Watson, and Pilgrim (1974), using data from the same experimental area, proposes that there is significantly less runoff from the pine forest than from the eucalypt forest. The majority of evidence from all parts of the world suggest no difference in water yield due to difference in species of mature forest (see Boughton, 1970).

There are plot and catchment experiments established in almost all States and Territories of Australia for study of the effects of soil conservation works and agricultural practices on water yield. But analysis has been given much less attention than collection of data. The meager evidence available in published reports suggests that practices such as fallow which affect evapotranspiration will have an identifiable effect on water yield, while structural works such as the construction of contour banks will not affect yield. Most studies are on small areas and there is an untouched problem of how to extrapolate experimental results to estimate the behavior of large heterogeneous catchment areas.

#### Summary of Water Yield

Where suitable overlapping records of runoff and rainfall are available, it is now possible to establish a rainfall-runoff relationship with considerable accuracy, using computer simulation of catchment water balance. In the absence of such records, there is doubt about the accuracy of runoff estimated from rainfall on ungaged catchments.

A number of studies and reviews of literature have been made to delineate the effects of land use on the water yield of catchments. It seems clear that practices which affect evapotranspiration, such as conversion from forest to pasture or fallow, will affect the volume of runoff or groundwater recharge. However, the available knowledge has not yet been incorporated into simulation models of catchment behavior or other methods of estimating catchment yield.

**FLOODS**

The tropical north of Australia and the east coast is subject to cyclonic storms which produce the most severe floods in these areas. The southern edge of the continent and Tasmania are more influenced by frontal weather systems of the mid-latitude temperate region.

Floods resulting from cyclonic storms are characterized by large volumes of runoff, frequently in the range 250-500 mm. For example, the January 1974 flood which devastated Brisbane produced 280 mm of runoff from an estimated 390 mm average rainfall over the 12,950 km<sup>2</sup> catchment area. Flood runoff from the 1,334 km<sup>2</sup> Stanley River sub-catchment of the Brisbane River valley was 455 mm from rainfall of 500 mm in this same storm (see Institution of Engineers, Australia, 1974, p. 47).

In such circumstances, the effects of land use on flood volumes and flood peaks are insignificant, as far as large catchments are concerned. The only significant effects on flood mitigation results from major dams. There are no single purpose flood control dams in Australia, but some urban water supply dams contain flood mitigation pondages. Similarly, some of the major irrigation dams have significant flood mitigation effects due to the temporary storage above spillway level of flood inflows. The following table shows the percentage reduction at nine of the major irrigation dams in Queensland by spillway surcharge without any special provision of flood pondage:

Dam	Catchment Area - km <sup>2</sup>	Design Inflow Storage m <sup>3</sup> /sec	Max. Spillway Discharge m <sup>3</sup> /sec	Percentage Reduction
Moogerah	225	6,020	740	88%
Tinaroo Falls	544	5,480	1,160	79%
Monduran	1,307	10,030	2,260	77%
Maroon	106	1,765	425	76%
Wuruma	2,316	12,710	3,810	70%
Leslie	603	6,640	2,150	68%
Beardmore	75,310	14,130	5,540	61%
Borumba	466	5,310	3,135	41%
Coolmunda	1,734	11,440	6,840	40%

There is no evidence in Australia to suggest that small dams spread throughout a large catchment will reduce flood peaks. Most informed opinion supports those studies in the USA which have shown no reduction in large floods by small dams on large catchments.

Synthetic unitgraph procedures have been developed in Australia by Eaton (1954), Coulter (1961), and Cordery (1967). In each case, the unitgraph parameters which determine the flood flow from rainfall input were related only to topographic features such as area, slope, length of the main stream, and channel roughness. In no case does land use enter the calculation of unitgraph parameter values.

Pilgrim (1966) compared 150 loss rate values from 24 Australian catchments with similar data from the United

States and New Zealand. The three sets of data showed remarkable agreement in the general order and distribution of values; however, the only factor which could be defined as affecting loss rate was season of the year. Winter floods in general tended to be associated with low loss rates and summer floods with high rates. The reasons for this are complex but probably include the effect of different rates of evapotranspiration on the antecedent wetness of the soil. Nothing has been established concerning how changes in land use affect loss rates.

Dunin (1965) reported a detailed study of the hydrology of five experimental catchments, 1.6 ha to 85 ha in area, operated by the Soil Conservation Service of Victoria. Conversion from native pasture to annual improved pasture resulted in a reduction in water yield but no discernible effect on flood flows. Other studies on experimental catchments in Australia have failed to clearly define any relationship of flood flows with land use.

In summary, the main factors which affect flood magnitude are the rainfall characteristics of the area, topographic features of the catchment, detention storages such as lakes or major dams, and to a lesser extent, season of the year because of its effect on antecedent moisture conditions. Although not related to range and forest management, the effect of urban development on increasing flood peaks is well known, and several methods of incorporating this effect into design calculations have been tested.

**EROSION**

**Rates of Erosion in Australia**

The sediment sampling practices of the main water resources authorities in Australia were reviewed 6 years ago in a report by the Australian Water Resources Council (1969b).

Data in this report show that the observed rates of sediment deposited in 13 Australian reservoirs ranged from 0.13 to 2.52 cubic meters of sediment deposited per annum per hectare of catchment, with an average value of 0.62. Only three values were higher than the average, and these were from storages in semi-arid areas. Dams of particular risk appear to be small water supply storages, and storages with semi-arid catchments, e.g. the Ord River dam.

Comment was made in the above-mentioned report that generally the rates of sediment deposition in reservoirs in Australia are not high. This is supported by Holeman (1968) who gave the following figures for average sediment yields of major rivers in the continents of the world:

	Sediment Yield m <sup>3</sup> /ha/year
Asia	5.59
North America	0.89
South America	0.58
Australia	0.42
Europe	0.33
Africa	0.26

The situation from the viewpoint of the Soil Conservationist is set out in a report by the Standing Committee on Soil Conservation (1971). This report contains the results of a survey of soil erosion in all States and Territories by members of the Standing Committee. For non-arid regions of Australia, some 600,000 km<sup>2</sup> or 30 percent of the area is affected to some degree by soil erosion. About one-third of the erosion is major erosion, and two-thirds minor erosion.

This report by the Standing Committee on Soil Conservation gives details of some of the major catchment protection work undertaken in Australia. The Eppalock Catchment Project in Victoria was the first time in Australia that funds were allocated for soil conservation in the catchment at the same time as approval was given for construction of a major dam. Expenditure on erosion mitigation was approximately \$1.1 million at 1971 prices. Catchment protection was undertaken by the Department of Agriculture, Western Australia and the Northern Territory Administration to protect the Ord River Dam against siltation. Since 1960, the Metropolitan Water, Sewerage and Drainage Board which provides Sydney's water supply has paid 50 percent of the cost of structural soil conservation works by landholders in the catchment area of the Warragamba Dam.

#### **State-of-the-Art of Erosion Management**

Management of erosion on water supply catchments is a practitioner's art in Australia, with little use made of scientific knowledge. It is not uncommon that real-life needs initiate practices based on rationalized experience before research can produce sufficient results to justify the actions. Erosion management is one of the last big areas of codified empiricism, untouched by scientific analysis, remaining in Australian hydrology.

In closed catchments, which are used only for the yield of water, fire is the main problem of managing erosion. Techniques for controlling burning to reduce fuel in litter are well established among foresters but not widely used on catchments by water supply authorities. A few individual observations of increased erosion following bushfires on catchments in Australia have been reported (Brown, 1972) but there has been no systematic study or attempt to codify the effects of fire on erosion in the manner of Rowe, Countryman, and Storey (1954) in California.

Catchments which consist of open grazing lands are usually managed by land and agriculture authorities to maintain productivity, and not by water supply authorities to control erosion. There have been some studies made of how to assess grazing capacity to avoid long term degeneration of land by erosion. Condon, Newman, and Cunningham (1969) describe a procedure for assessing the grazing capacity of arid lands in Central Australia. This empirically derived procedure is based on average annual rainfall, soil type, topography, percentage area of salt lake and unstable hills, tree density, and condition of land. Costin, Wimbush, and Kerr (1960) relate erosion to percentage ground cover in the mountain country of the Australian Alps which is an important catchment area providing 25 percent of the annual yield of the Murray River from 1 percent of its catchment area.

Some attention has been given to adopting the Universal Soil Loss Equation (Wischmeier and Smith, 1965) for use in Australia. In Queensland, an analysis of rainfall records was made in 1969-70 to derive values of the rainfall erodability index from this equation for all areas of the State (White and Swartz, 1972); and soil erodability indices are being derived from rainfall simulator experiments by the Department of Primary Industries and the Queensland Agricultural College at Gatton (Pauli, 1973, 1974). A major problem is the lack of data on sediment movement which might be used for analysis. A few records of soil loss from small plots are available in New South Wales, but very few measurements of soil loss from experimental catchments have been made.

Eastgate (1969) has tested the soil protective characteristics of some Australian grasses and has set out details for use in design of waterways. This is one aspect of erosion management where Australian research (albeit based on a United States precedent) has provided some fundamental data on hydraulic characteristics and erodibility, with broad application in practice.

Forested areas in water supply catchments in Australia are usually managed as production forests and rarely as protection forests. The main problem of forests in water supply catchments in Australia is concerned with the effects of forestry operations such as clearing for plantations, logging, and construction of access roads on water quality particularly turbidity.

Some forestry operations ignore even the elements of soil conservation which have been common knowledge for almost half a century. Establishment of softwood plantations on rectangular grids, without regard for contour or land form, are difficult to explain in this day and age. Little scientific knowledge would be required to eliminate the worst erosion problems arising from forestry practices in Australia.

It would be wrong to imply that forestry operations are the sole cause of erosion on water supply catchments.

The issue of leases for bauxite mining in catchments providing water for metropolitan cities (as in Perth) or coal mining operations immediately adjacent to the stored waters of a city's supply (as near Sydney's Warragamba Dam), are other examples of the type of erosion management problems which occur on our catchment areas.

**SUMMARY AND CONCLUSIONS**

Where a few years or more of runoff record are available, it is now relatively easy to establish a rainfall-runoff relationship, either to estimate the temporal pattern of water yield from the catchment or the long term frequency distribution of floods. In these circumstances, the land use of the catchment is automatically allowed for when establishing the relationship.

Where no runoff records are available, it is much more difficult to estimate the yield or flood characteristics of an ungauged catchment. Similarly, there are no established procedures for estimating the hydrologic effects of a future change from present land use, even on a gaged catchment where records of past behavior are available.

The effects of range and forest management on erosion are well known in qualitative terms from rationalized experience of conservation activities over many years. But at the present time, there is no established knowledge in Australia for quantitative management of sediment production, transport, and deposition. Research activity which could improve this situation is minimal.

Considering research over the whole field of runoff and erosion, most research effort in Australia would be directed towards water yield and least effort towards erosion. When it is considered that the factors which influence the overall water balance and water yield are best understood and those which influence erosion are least understood, it seems that research interest is attracted to those areas where some success seems most likely.

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# Hydrologic Modeling of Rangeland Watersheds

*J. Paul Riley and Richard H. Hawkins\**

## INTRODUCTION

The problems of managing water resource systems are basically those of decision-making based upon considerations of the physical, biological, economic, sociological, and other processes involved. These processes are strongly interrelated and constitute a dynamic and continuous system. Any combination of these interrelated system variables yields a management solution. In recent years, the advent of electronic computers has stimulated the use of modeling analysis for planning and management of large and complex systems. In essence, the model is intended to reproduce the behavior of the important system variables of the prototype under study.

Once a prototype system is identified, the various processes in the system may be represented by either physical or mathematical models. Figure 1 indicates the two general categories of mathematical modeling as being simulation and mathematical programming. Mathematical programming is an optimizing procedure whereby a solution is sought in terms of a specific objective function. Frequently, this procedure requires considerable simplification of the real system. Simulation is an attempt to represent as realistically as possible (or necessary) the processes of the real world. Simulation by physical models has found application to many practical problems, such as the design of highway bridges and hydraulic structures. However, for complex systems such as those encountered in water resources management, mathematical simulation often proves to be the only feasible tool for predicting the system behavior. For this reason, this paper places emphasis on a discussion of mathematical simulation, whereby models are synthesized and solved by means of electronic computers.

Mathematical simulation is achieved by using algebraic relationships to represent the various processes and functions of the prototype systems, and by linking these equations into a systems model. Hopefully, simulation

models have three basic properties: realism, precision, and generality.

Thus, computer simulation is basically a technique of analysis whereby a model is developed for investigating the behavior or performance of a dynamic prototype system subject to particular constraints and input functions. The model behaves like the prototype system with regard to certain selected variables, and can be used to predict probable responses when some of the system parameters or input functions are altered.

As illustrated by Figure 1, it is possible to employ either stochastic or deterministic techniques, or various combinations of both, in the representation of a system. The approach which is adopted is dependent upon a number of conditions including availability of information about the system and the kinds of problems which the model is required to solve. The predictive power of the model within the system response space usually will vary with the degree to which the model is stochastic or deterministic. The predictive capability of a model in terms of the physical interpretation employed in its development (stochastic to deterministic) is illustrated schematically by Figure 2.

## SOME ADVANTAGES OF SIMULATION MODELING

Basically, computer simulation models are advantageous because of:

### 1. The answers they give

- a. Some answers just otherwise unattainable.
- b. Evaluation of wide array of alternatives.
- c. Non-destructive testing.
- d. Distribution of errors and judgment variations among several coefficients.
- e. Allows assembly of many processes, etc., into an integrated package.

### 2. The questions they ask

- a. Indications are provided in quantitative terms of progress toward system definition and con-

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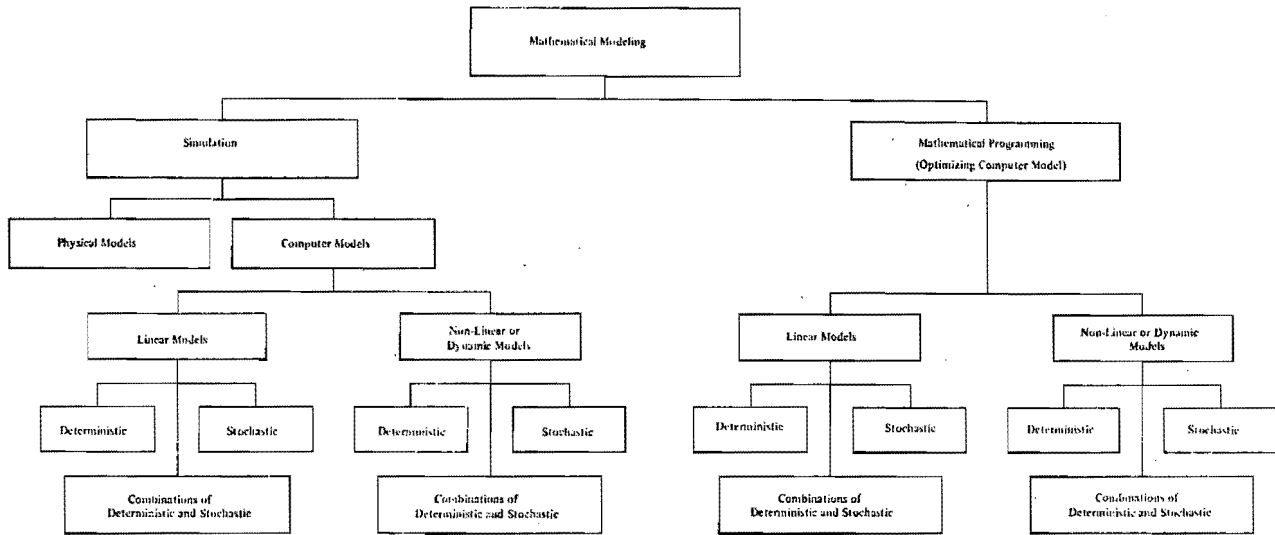


Figure 1. A classification diagram for mathematical modeling.

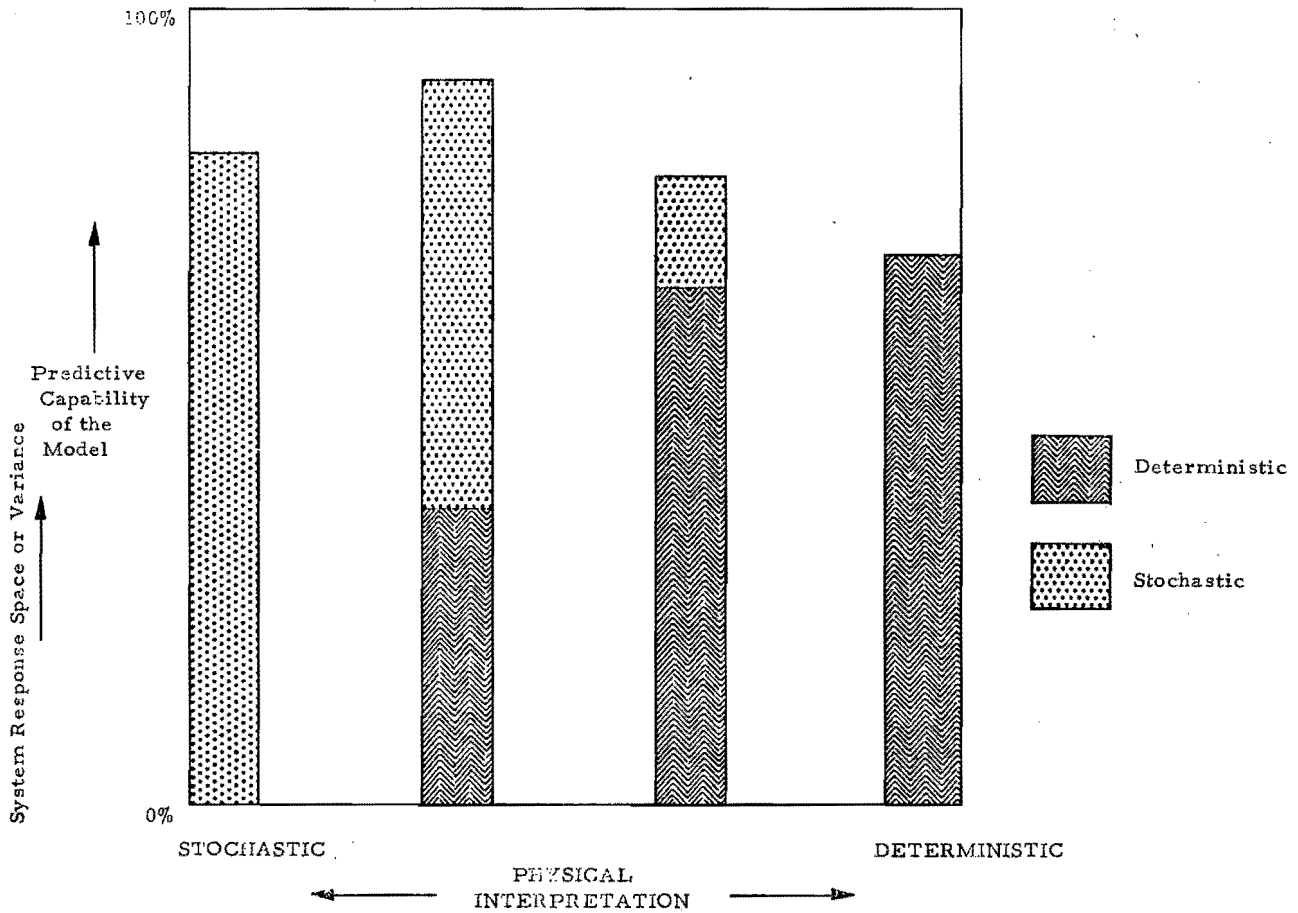


Figure 2. A schematic representation of the predictive capability of a model in terms of the physical interpretation employed in its development.

- ceptual understanding.
- b. The relative importance of various system processes and input functions is suggested.
- c. Priorities are suggested in terms of planning objectives and data acquisition.
- d. A clear identification is required of problems and objectives associated with the system being studied.

### 3. The insights they provide

- a. A basis for coordinating information and efforts of personnel across a broad spectrum of scientific disciplines.
- b. Models are a very effective teaching device.

In summary, a model provides for maximum utilization of a given information base or data pool in terms of predictive capability of system performance. Each system performs with a total response space, and the greater the information base, the greater is the possibility of developing a model which accurately predicts system performance within this space.

## THE PROCESS OF SIMULATION MODEL DEVELOPMENT

As already suggested, a model is an abstraction from reality, and in this sense is a simplification of the real world which forms the basis of the model. The degree of simplification is a function of both intent or planning and knowledge about the real world. Forrester (1961) pointed out that verbal information and conceptualization may be translated into mathematical form for eventual use in a computer. Therefore, the model development process should proceed essentially from the verbal symbols which exist in both theoretical and empirical studies to the mathematical symbols which will compose the model.

The development of a working mathematical model requires two major steps. The first step is the creation of a conceptual model which represents to some degree the various elements and systems existing in the real world. This conceptualization is based on known information and hypotheses concerning the various elements of the system and their interrelationships. In general, the conceptualizations and hypotheses of the real world of a particular study was formulated in terms of the available data. Efforts are made to use the most pertinent and accurate data available in creating the conceptual model. As additional information is obtained, the conceptual model is improved and revised to more closely approximate reality.

The second major step in the development of a working mathematical computer model is between the conceptual model and the computer or working model itself. During this step an attempt is made to express in both mathematical and verbal forms the various processes and relationships identified by the conceptual model. Thus, the strategy involves a conversion of concepts concerning

the real world into terms which can be programmed on a computer. This step usually requires further simplification, and the resulting working model may be a rather gross representation of real life.

Dr. Ven T. Chow has compared the loss of information, first between the real world and the conceptual model, and second, between the conceptual model and computer implementation to filtering processes as depicted by Figure 3 (Riley, 1970). The real world is "viewed" through various kinds of data which are gathered about the system. Additional data usually produce an improved conceptual model in terms of time and space resolutions. The improved conceptual model then provides a basis for improvements in the working model. Output from the working model can, of course, be compared with corresponding output functions from the real world, and if discrepancies exist between the two, adjustments are indicated in both the conceptual model and the working model. The important steps involved in the process of model development are depicted by the diagram of Figure 4. The paragraphs which follow are devoted to a brief discussion of the steps indicated by this diagram.

### Identification of Objectives

Clearly, the starting place in a systems approach to water resources development would suggest a clear delineation of the different purposes and objectives in water development. What do we want to accomplish? Why engage in control and management of the resource? In the final analysis it becomes apparent that there is a hierarchy of related objectives which pyramid down from some overall human objective. For example, engineering objectives regarding storage, regulation, and distribution of water is a logical consequence and component of some higher order objectives based on human factors. These objectives are all related horizontally and vertically such that a change in objectives, criteria, and priorities at one level may require changes in others. In this sense we have a "system" of objectives which serve as guides and criteria in planning and development of the resource system itself.

There have been many instances of water development where this unified spectrum of objectives has not been appreciated. Objectives have sometimes been limited to considerations of a particular component of development projects and have not been properly integrated with the all important human objectives. Objectives which center around building of a dam, for example, without a thorough appreciation of the ultimate social and economic objectives to be achieved by its operation have ultimately proved to be of little stimulus to the general economy. We may design and build magnificent dams and canals which are necessary to control, convey, and manage water so as to bring land under irrigation. However, if the lands to be served are inherently unproductive, or if the potential irrigator has not been trained or experienced in irrigation practices essential for sustained irrigation agriculture, or if

credit and marketing problems have not been considered, we may have wasted resources in the construction of the dam without ever accomplishing the real objectives of feeding people.

**System Identification**

The basis of system identification is the conceptual model of the real world developed through various kinds of data which are gathered about the system. In a sense, points at which the system is monitored may be regarded as being "windows" through which the dynamic operation of the real world system is observed at a particular point in space and perhaps in time.

The spacing of these observations in the space and time dimensions largely determine the refinement of the conceptual model in terms of actual or real world conditions. For example, a gross conceptual model which is intended to represent the basic structure of hydrologic-biologic world is shown by Figure 5. A close examination of any one of the three major components depicted by this figure would reveal some of its internal processes, and thus lead to an improved conceptual understanding of the system. For example, a relatively detailed conceptual model of a typical hydrologic system is illustrated by the block flow diagram of Figure 6. In this diagram the blocks indicate storage locations within the system and the lines represent various processes by means of which water is transferred from one storage location to another. As the real world system is better understood, the conceptual

model is adjusted to coincide more closely with the system of the real world. In this case, the filtering loss is lessened between the real world and the conceptual model, as indicated by Figure 3.

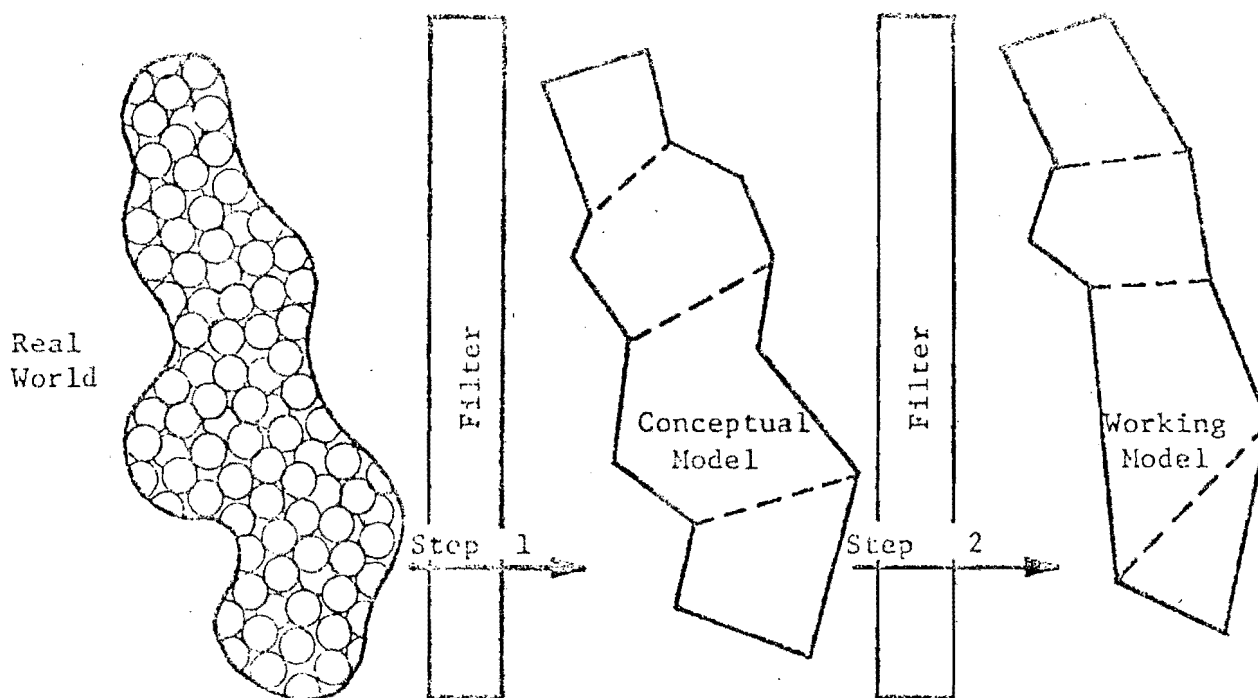
**Evaluation and Analysis of Available Data**

This is one of the most important and time-consuming steps in the simulation of water resource systems. As already indicated, the data provide an understanding of the real world, and thereby establish a basis for evaluating model performance. The accuracy of predictions from a particular model are governed to a large degree by the reliability of the information on which the model is based and the accuracy of the data which are input to the model to provide the predicted output functions.

**Model Formulation**

Model formulation is the step between the conceptual model and the working model indicated by Figure 3. The form of the model which is used is dependent entirely upon the requirements of the problem (the objectives) and the data which are available for the study. The flow diagram of Figure 4 indicates four basic model categories, namely, distributed parameter, lumped parameter, stochastic, and deterministic.

In general terms, the mathematical representation of natural hydrologic systems may be achieved by means of either a lumped parameter model or a distributed



**Figure 3. Steps in the development of a model of a real world system.**

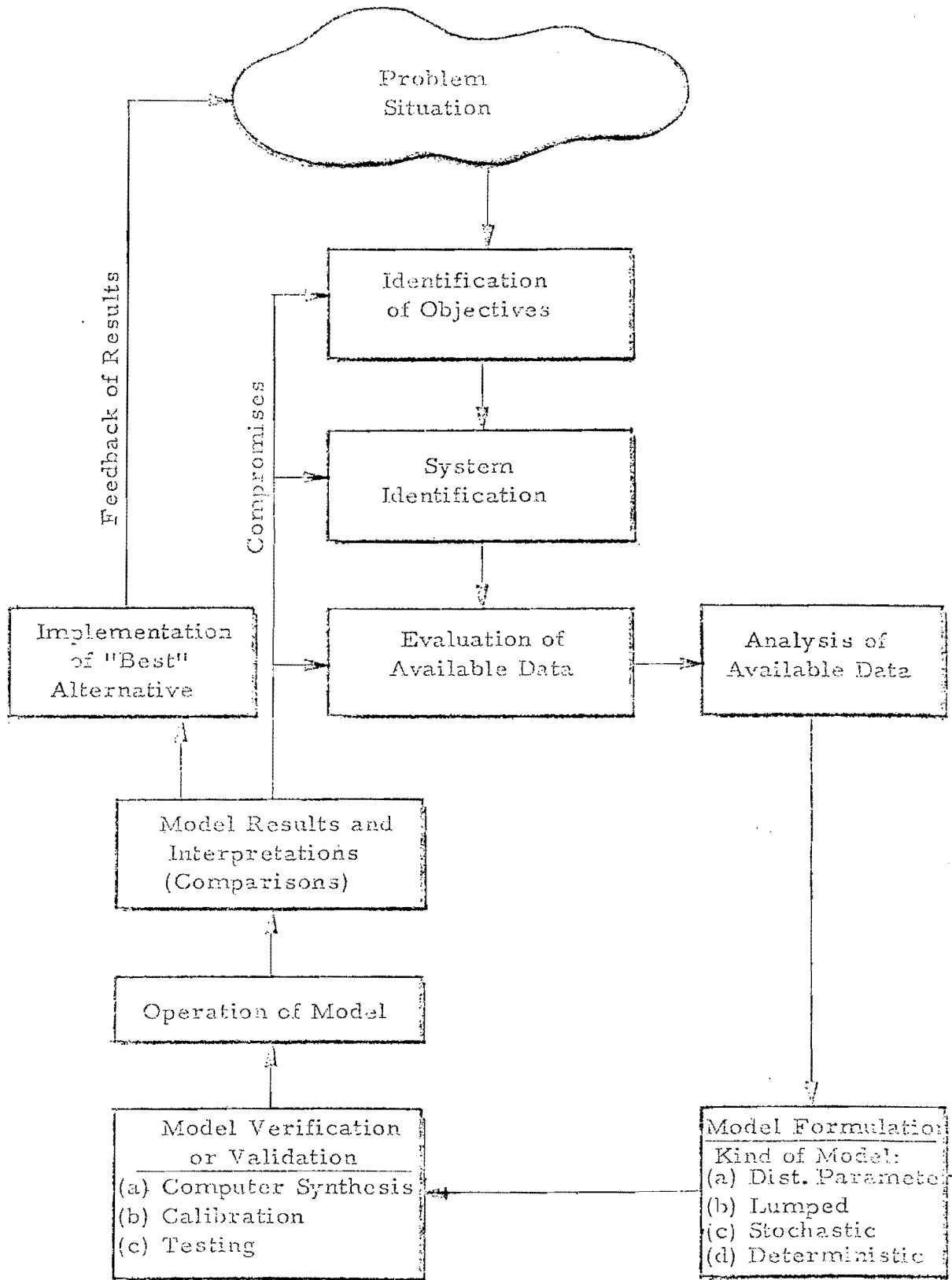


Figure 4. Steps in the development and application of a simulation model.

parameter model (Chow, 1967a, b). In addition, processes within the hydrologic system may be represented by relationships which are deterministic or stochastic or a combination of the two (Figure 2). For example, a system might be represented as a lumped parameter model with stochastic processes, or as a distributed parameter model with deterministic processes. For lumped parameter models, space coordinates, or position, is neglected, and all parts of the system being simulated are regarded as being at a single point in space. On the other hand, if the space dimension is represented by various distributed points or areas within the internal space of the system, a distributed parameter model is constituted.

With reference to distributed and lumped parameter models, practical data limitations and problem constraints require that increments of time and space be considered during model design. For example, a monthly time increment might be entirely satisfactory for problems concerned with reservoir storage requirements for irrigation. However, for problems which deal with spillway design capacities, a daily, or even hourly, time increment might be needed. In addition, data, such as temperature and precipitation readings, are usually available as point measurements in terms of time and space, and integration

in both dimensions is usually accomplished by the method of finite increments.

The complexity of a model designed to represent a hydrologic system largely depends upon the magnitude of the time and spatial increment utilized in the model. In particular, when large increments are applied the scale magnitude is such that the effect of phenomena which change over relatively small increments of space and time is insignificant. For instance, on a monthly time increment, interception rates and changing snowpack temperatures are neglected. In addition, the time increment chosen might coincide with the period of cyclic changes in certain hydrologic phenomena. In this event net changes in these phenomena during the time interval are usually negligible. For example, on an annual basis, storage changes within a hydrologic system are often insignificant, whereas on a monthly basis, the magnitude of these changes are frequently appreciable and need to be considered. As time and spatial increments decrease, improved definition of the hydrologic processes is required. No longer can short-term transient effects or appreciable variations in space be neglected, and the mathematical model, therefore, becomes increasingly more complex with an accompanying increase in the requirements of computer capacity and capability.

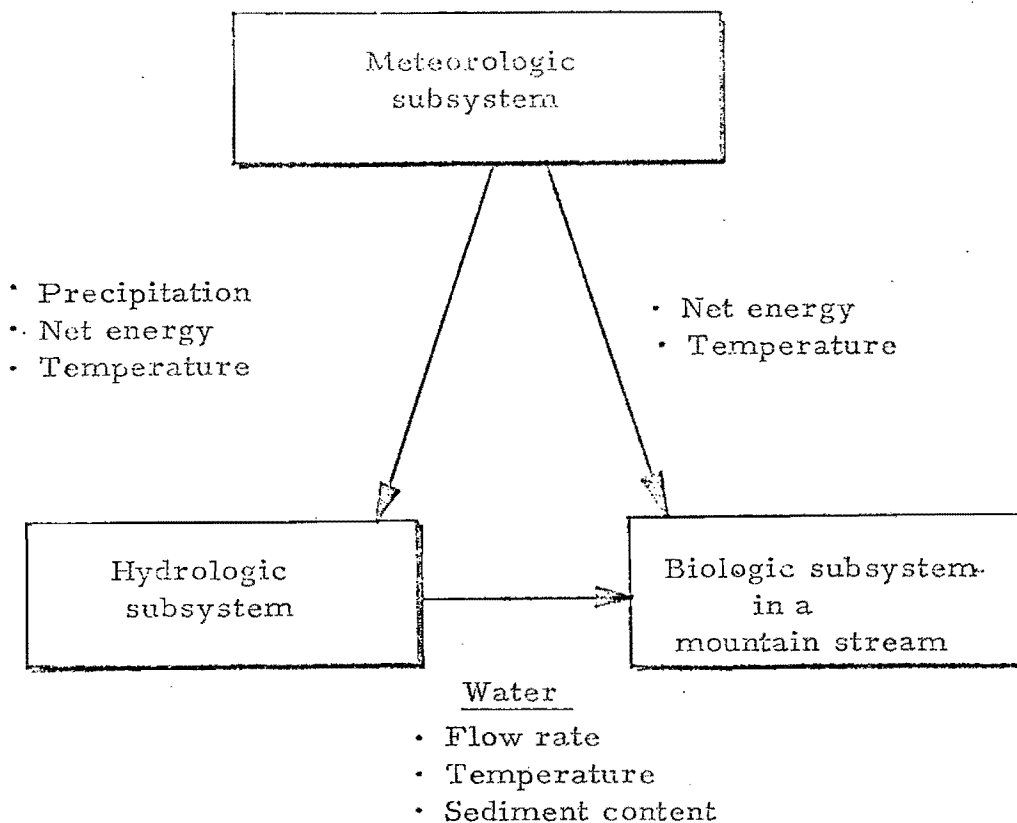


Figure 5. A simplified model of an aquatic ecosystem showing component subsystems and linking processes.

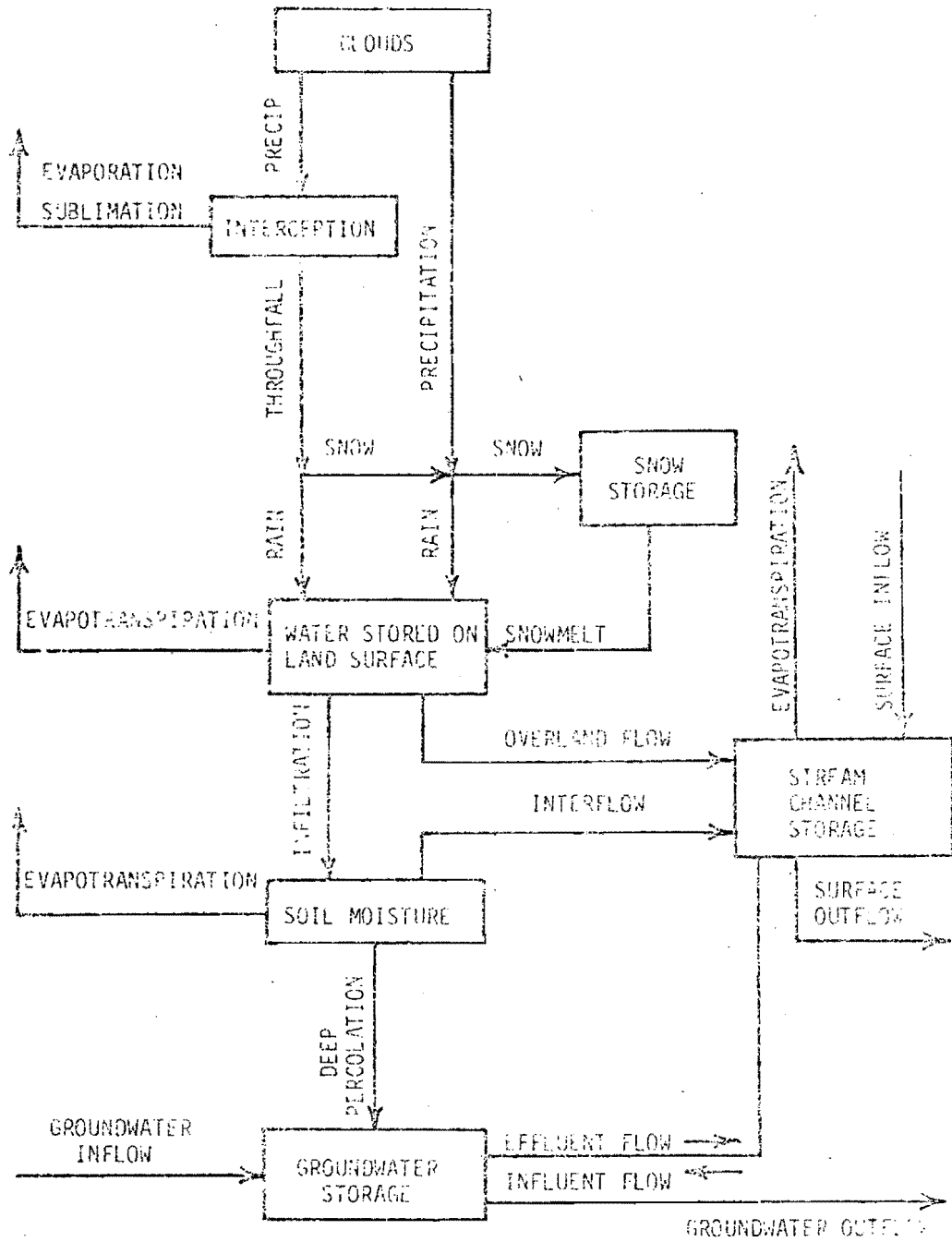


Figure 6. A flow diagram of the hydrologic system within a typical drainage basin.

## Model Verification

### *Computer synthesis*

A computer model of a hydrologic system is produced by programming on a computer the mathematical relationships and logic functions of the hydrologic cycle. The model does not directly simulate the real physical system, but is analogous to the prototype, because both systems are described by the same mathematical relationships. A mathematical function which describes a basic process, such as evapotranspiration, is applicable to many different hydrologic systems. The simulation program developed for the computer incorporates general equations of the various basic processes which occur within the system. The computer model, therefore, is free of the geometric restrictions which are encountered in simulation by means of network analyzers and physical models. The model is applied to a particular prototype system by establishing, through a verification procedure (sometimes called validation or parameter identification), appropriate values for the "constants" of the equations required by the system.

### *Model calibration*

A general hydrologic model is applied to a particular basin through a verification procedure whereby the values of certain model parameters are established for a particular prototype system. Verifications of a simulation model is performed in two steps, namely, calibration, or parameter identification, and testing of the model. Data from the prototype system are required in both phases of the verification process. Model calibration involves adjustment of the model parameters until a close fit is achieved between observed and computed output functions. It therefore follows that the accuracy of the model cannot exceed that provided by the historical data from the prototype system.

### *Testing the model*

As indicated in the previous section, model verification involves the two steps of calibration and testing. Model calibration is achieved by a fitting process which establishes the model parameters for a particular set of data from a given hydrologic unit. Model testing involves using a second and independent set of data from the same hydrologic unit, and again operating the model in order to determine the level of agreement between the observed and predicted (or computed) output functions. Thus, model testing is simply an independent test of results achieved under the calibration phase.

## Model Results and Interpretations

The model is, of course, operated during the verification procedure, and at this time comparisons are made to test the ability of the model to represent the system of the

real world. It is very possible that these tests indicate that some adjustments are necessary, either in the data on which the model is based, or in the structure of the model itself. The various options associated with this looping, or "feedback," procedure are indicated by the flow path labeled "compromises" on the diagram of Figure 4. When suitable model verification has been achieved, the model is ready for further operations involving management and sensitivity studies.

### *Sensitivity studies*

A sensitivity analysis is performed by changing one system variable while holding the remaining variables constant and noting the changes in the model output functions. If small changes in a particular system parameter induce large changes in the output or response function, the system is said to be sensitive to that parameter. Thus, through sensitivity analyses, it is possible to establish the relative importance with respect to system response of various system processes and input functions. This kind of information is useful from the standpoint of system management, system modeling, and the assignment of priorities in the collection of field data.

### *Management studies*

A simulation model does not of itself produce an optimum solution in terms of management objectives. The technique does, however, facilitate a rapid evaluation of many possible management alternatives. An analytical optimizing procedure used in conjunction with a simulation model could produce system optimization in terms of a specific objective function. However, the simulation model of itself is capable of providing the water resource planner and manager with the kind of information needed to facilitate the selection of a "best" alternative from a very large number of possible choices. Though perhaps not directly a part of the simulation or modeling process, the loop should be closed, so to speak, by the feedback of results from the implementation of the alternative selected to the initial problem situation. This suggested feedback loop is illustrated in Figure 4.

## AN EXAMPLE

### **A Small Watershed Model**

With the preceding background, the actual creation—on paper—of a watershed hydrology system should proceed without difficulty. For what is to follow, we shall use as an example a deterministic, lumped small watershed rainstorm hydrograph model used in several teaching and research efforts at Utah State University. It is shown in diagram form in Figure 7.

The model is drawn from a direct tank analogy of watershed hydrology, as just presented by Dawdy and O'Donnell (1965), and is similar to the digital storm runoff model used by Dawdy, Lichty, and Bergeman (1972).

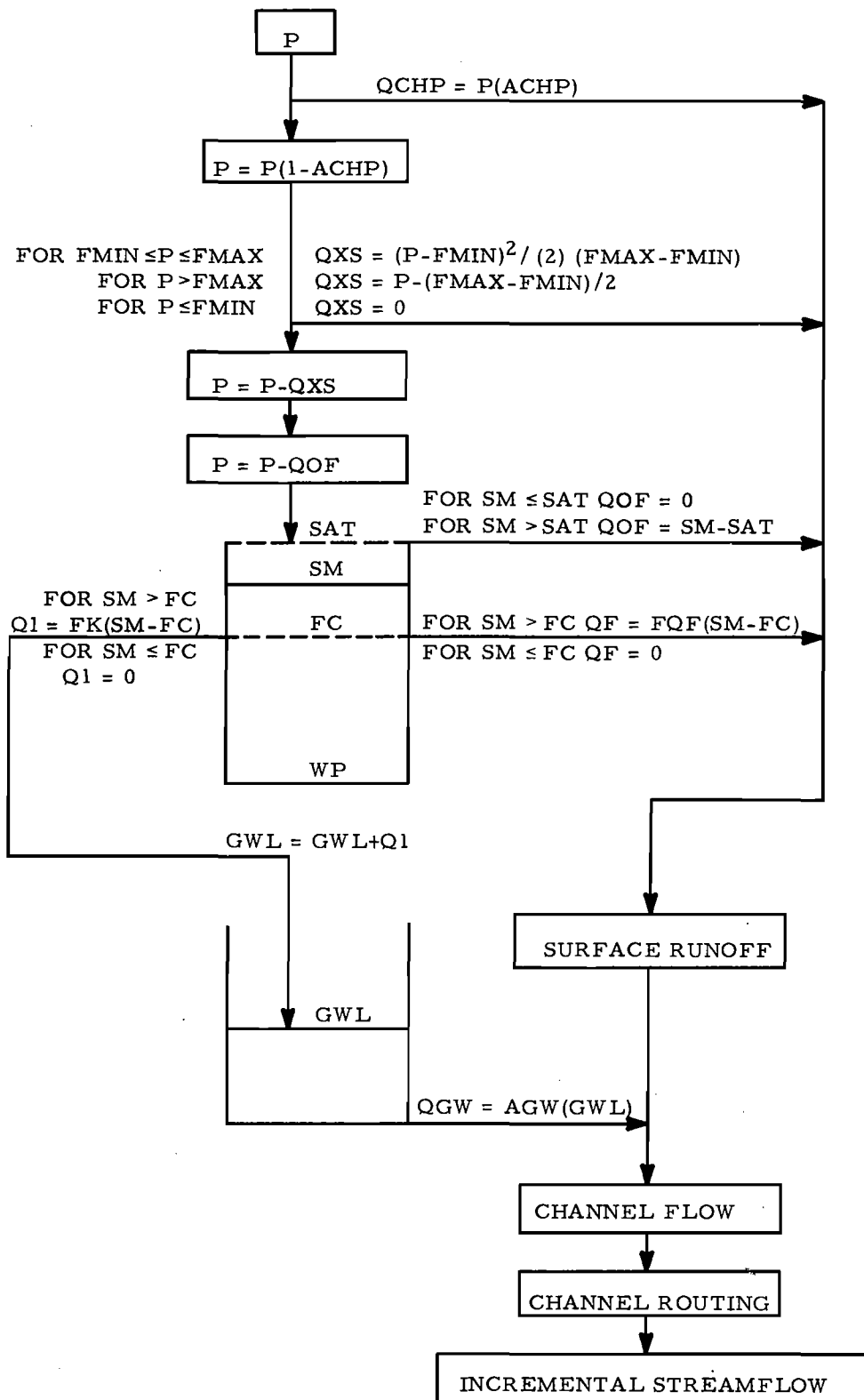


Figure 7. Diagrammatic representation of a lumped deterministic watershed model for rainstorm runoff.



Although such similarities smack of plagiarism, adherence to the conceived realities of the hydrologic cycle inevitably draws hydrology models toward a common structure.

There are several features of the model which should be detailed. First, there is no snowmelt routine, insofar as the model is intended to deal only with summer rainstorms. This is a major simplifying item, as snowmelt hydrology occupies a major portion of most "full feature" models. Secondly, evapotranspiration (ET) is ignored, and plays no role in the model. This is done on the following rationale: (a) it is usually small during a storm duration, and the state of the driving variables operating them (overcast sky, high relative humidity, and cooler temperatures) militate against evapotranspiration; (b) insofar as the real ET is small, it could be trivial when compared to the error of rainfall measurement. There is also some pragmatic reasoning: Inclusion of ET would require short duration temperature/radiation/cloud cover data, which is not always available; and the model, as shall be seen, seems to work without the complication of evapotranspiration.

The model uses linear reservoirs and transfer functions throughout, and avoids an abrupt threshold infiltration by assuming a linear distribution of time and soil moisture independent infiltration rate across the watershed. This is a not uncommon ploy, and was also used by Dawdy et al. (1972). A channel routing procedure may be used, consisting essentially of an outflow translation hydrograph (a "unit" hydrograph) as also used, for example by Williams and Hann (1973). Also, vegetative interception storage is not included. If desired, an equivalent storage can be simulated by an adjustment of initial soil moisture level. The model programs easily in FORTRAN or BASIC, and has been fit to a desktop programmable maxi-calculator.

The model, then, is operated by what might be best described as an accounting procedure. A set of initial conditions are established or assumed (soil moisture and groundwater storage at storm initiation), input data are deposited by increments ( $\frac{1}{2}$  hour), and an accounting is successively made. Water is diverted to or moved from storage to storage in accordance with the model assumptions shown, and a new set of storages determined at the end of each time increment. As shall be seen, a hydrograph results.

#### **Calibration to Chicken Creek**

Calibration is a procedure of determining the optimum set of model parameters from a set of field data on real watersheds. It is analogous to a least squares determination of coefficients for a multiple regression. Unfortunately, it is only analogous to that, in fact, it is neither as orderly nor as automatic as the most ornate least squares procedure.

The West Branch of Chicken Creek is a 217 acre (87.8 ha) small watershed in Utah's Wasatch Front, east of Farmington, Utah, about 20 miles (35 km) northeast of Salt Lake City. It receives about 45 inches (1140 mm) of precipitation annually, mostly in the form of snow, which results in about 19 inches (480 mm) of runoff. Occasional summer thunderstorms produce short duration hydrographs of low volume, but sometimes intense rates of runoff. The watershed ranges in elevation from 7,550 ft (230/m) to 8,396 ft (2,559 m). It is a part of the U.S. Forest Service, Davis County Experimental Watershed (DCEW), historically notorious for a classical sequence of land abuse, flooding, and debris production. Instrumentation includes a recording rain gage network and a flume at the watershed mouth. A summary paper on Chicken Creek has been prepared by Johnston and Doty (1972).

The data from several summer storms was fit to the model, and through a calibration procedure—which rests heavily on a trial and error routine—a best fit series of coefficients determined for the storms. These are shown in Figure 8. It should be emphasized that these are the same coefficients from storm-to-storm; only the initial conditions and inputs vary. Naturally, much better fits can be made on individual storms. A root-mean square error term was used as the goodness of fit criteria. The results of calibrations are given in Table 3.

It should be evident from Figure 8 that the model's output pays a price for its simplicity. The response is not ideal, there are obvious inputs without corresponding outputs, and vice versa. Further model refinement, which may be justified, would add more coefficients to be determined in the calibration procedure. Further structural changes would require justification and would also demand accompanying coefficients.

Some interesting insights to the hydrology of Chicken Creek arose from the modeling study. For the storms studied, storm runoff is in general a very small part of the input rainfall; usually less than 1 percent. It is composed entirely of channel interception and quick flow. In no case was an infiltration excess and overland flow phenomenon apparent.

This suggests some interesting hypotheses on the role of classical small watershed hydrology, in the situation represented by Chicken Creek. For example, a general mismatching exists between meteorological inputs and the infiltration characteristics, and thus channel formation and stability evolves accordingly. This placid state of affairs continues until the unusual extreme event does eventually come along, when infiltration capacities are finally exceeded; storm runoff is enlarged perhaps a hundred-fold and surface erosion, channel erosion, and channel scour results. This explanation or a variety of it fits nicely into the observed floods and erosion sequence in the Davis County Experimental Watersheds.

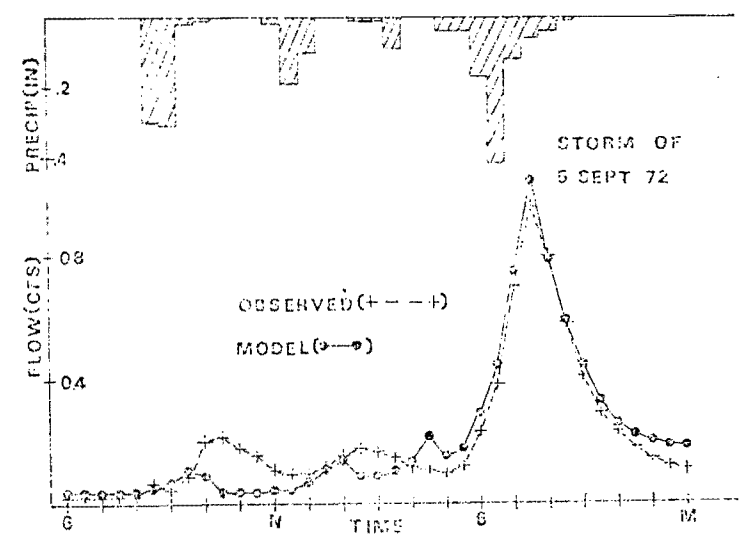
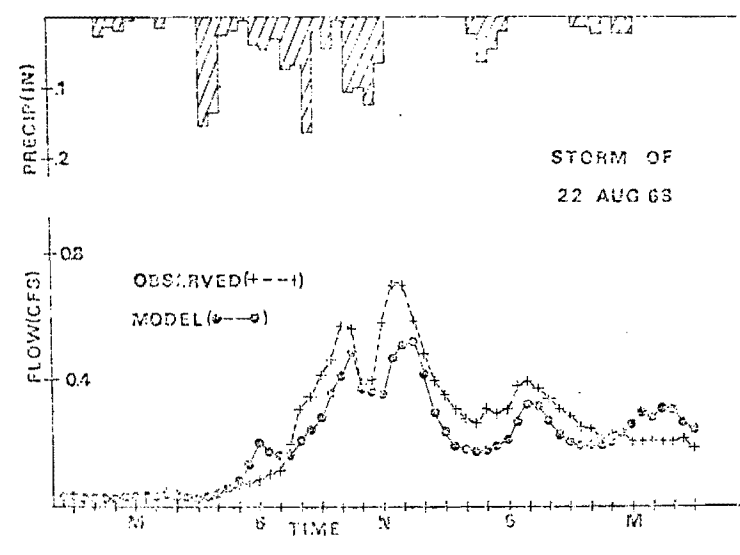
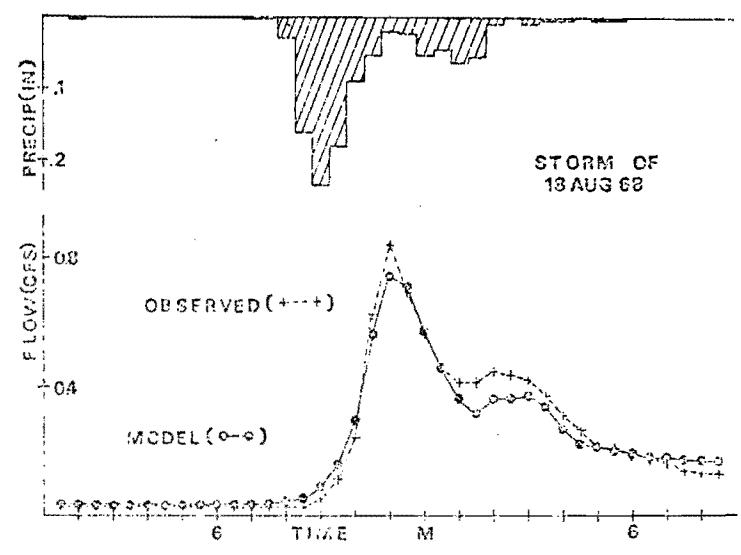
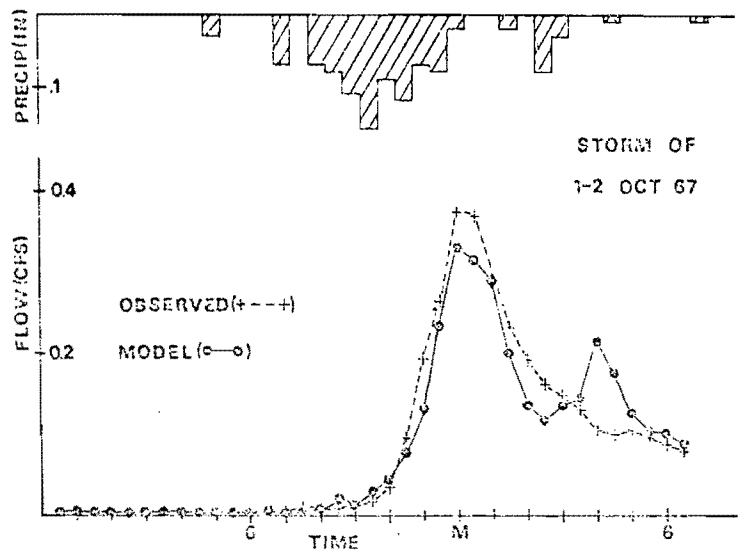


Figure 8. Recorded and model fit hydrographs for the West Branch of Chicken Creek, Davis County Experimental Watersheds, Utah. Calibration coefficients are given in Table 2.

From the standpoint of model calibration, the infiltration conclusions leave an awkward situation: the infiltration parameters are not defined, since no event brought this process into play. A lower limit to infiltration capacity can then be defined only as greater than the maximum input intensity. Also, saturation soil moisture could not be quantitatively defined, as it was apparently never attained. Such real limitations of digital modeling argue the use of extreme events in calibration. Coefficient values for soil saturation and infiltration properties shown in this paper are thus in part either subjective estimates or dummy values, and without wholly valid justification.

#### Application to "Range" Conditions

Insofar as the model coefficients infer a physical interpretation, they might be varied to reflect a specific set of land conditions, e.g., a rangeland watershed. This prospect raises an interesting point worthy of adequate independent discussion: i.e., is the term "range watershed" hydrologically valid? Is there a peculiar set of hydrologic processes and conditions which prevail on rangelands? Do rangeland watersheds have a meaningful set of independent characteristics? This provokes further inquiry: what exactly is rangeland; a distinct ecological set or a man-imposed land-use definition? We will not follow the inquiry into its tempting details; it is more instructive here, and

not entirely in error, to sidestep this semantic issue and make some simplifying assumptions.

Table 1 contrasts the characteristics and specifications for range and forest watersheds in idealized terms for general natural conditions, and with a modeling effort in mind. It is not intended to be an all-encompassing last word, but rather an illustrative set of distinctions on a comparative basis. It is not at all difficult to cite specific exceptions to the listing.

A hypothetic change to rangeland conditions with all its necessary consequences can now be evaluated by altering the coefficients in accordance with Table 1, and using a courageous dollop of judgment. Such an approach has been used to estimate the effects on runoff from wildfires (Fleming, 1971; Shih, et al., 1972), urbanization (Crawford, 1969; Riley et al., 1974), channel improvements (Crawford, 1970), and timber harvesting (Leaf and Brink, 1972). The parameter revision to represent a typical rangeland situation is given in Table 2.

The original storms were rerun through the model with the rangeland coefficients and the results are shown in Figure 9. The comparisons are difficult because there were different initial conditions assumed for the rangeland situation, i.e., low soil moisture and no baseflow.

**Table 1. Generalized and idealized contrasts between forest and range conditions.**

Item	Range	Forest
<u>Precipitation</u>		
Annual Rainstorms Intensities	Low to moderate Often entire water supply High, short duration	Moderate to high May include rain and snow Longer durations, ground intensities modified by cover
Snow	May be absent	Often a significant role
<u>Soil and Surface Properties</u>		
Surface texture	Fine	Coarser
Depth	Shallow	Deep
Presence of pans	Sometimes	Seldom
Organic Matter	Poorly incorporated	Well humified
General development	Poorly developed accumulation horizons grass and/or shrubs	Well developed leached horizons, trees and grass and understory vegetation
Ground cover	Often sparse	Seldom sparse
Intercepting canopies	Single	Often multiple
<u>Runoff and Hydrology</u>		
Infiltration rates	Low	High
Overland flow	Common during rainstorms	Rare
Base flow	Seldom, intermittent	Typical condition
Permanent stream	Absent or intermittent	The usual case
Water quality	Often salty, warm, etc. High natural erosion	Usually good quality, low natural erosion, high if aggravated
<u>Land Use</u>	Consistent annual harvest	Sporadic, occasional harvest at rotation
<u>Initial Conditions</u>		
Soil moisture	Low	Variable
Groundwater	None	None or some
Channel surface area	None	Small, but present

However, a summary in more conventional hydrologic terms is given in Table 3. Note the greater reaction to rainstorm for the range condition. Needless to say, the conclusions are only as reliable as the model structure is valid, and as the coefficients are trustworthy. We have, however, reduced the points of discussion to those questions, and we have some insights to the workings of the system. Our professional judgments on ". . .the effects of. . ." a land treatment or condition on runoff are now tempered to the point discussing more exact watershed processes and parameter values. To many this is a vast improvement.

**SOME QUESTIONS CONCERNING SIMULATION MODELING**

The output of a simulation model hangs heavily on three primary items: (1) model structure; (2) the model

parameters; and (3) initial conditions. These determinations are made difficult by the modeler's preconceptions, scarcity of data, poor quality data, and lack of areal and temporal resolution. To some degree, this is akin to a regression or curve fitting situation. Thus, attempts at modeling are based partially on "feel" and on the intuition of the modeler.

While it is difficult for the basic structure to vary far from the hydrologic cycle, the detail, exact processes, interactions, and resolution necessary for faithful representation are subject to some debate. Models are fit to data, assumptions are made, shortcuts are affected, with no actual check on the veracity of the internal fit. Critics of modeling accuse it of being subjective, black box dial twisting, not subject to unique solutions, and a collection of nonsense coefficients.

**Table 2. Parameter and initial conditions (coefficients) values used for forest and range watersheds.**

Parameter					
Symbol	Description	Units	Range	Forest <sup>a</sup>	Comments
ACHP	Channel Interception Fraction	in/in	0	0.00066	
FMAX	Maximum watershed infiltration rate	in/1/2hr	4	10 <sup>b</sup>	
FMIN	Minimum watershed infiltration rate	in/1/2hr	0.25	1 <sup>b</sup>	
SAT	Soil water content at saturation	in	7	7 <sup>b</sup>	
FC	Soil water content at field capacity	in	5	5	
WP	Soil water content at wilting pt.	in	0	0	
FQF	Fraction of soil water (> FC) that becomes quick flow	in/in	0.0020	0.0039	
FK	Fraction soil water (> FC) that contributes to groundwater reservoir	in/in	0.15	0.445	
AGW	Groundwater reservoir recession coefficient	in/in	0.00028	0.00028	
SMO	Soil water content at beginning of storm event	in	Variable		Calibrated for individual storm
GWLO	Groundwater content at beginning of storm event	in	0	Storm Specific	Calibrated for individual storm

<sup>a</sup>Parameter (coefficient) values from west branch Chicken Creek calibration.

<sup>b</sup>See narrative in text.

**Table 3. Model performance summaries: Forest and Range conditions.**

Item	Units	1-2 Oct. 1967		18 Aug. 1968		22 Aug. 1968		5 Sept. 1972		
		Forest	Range	Forest	Range	Forest	Range	Forest	Range	
Storm Rainfall	Inches	1.050		1.074		1.632		1.960		
Max. Intensity *	In/Hr	0.320		0.470		0.309		0.820		
Storm Runoff	10 <sup>-3</sup> In.	6.07	25.25	6.37	31.10	11.55	38.84	34.49	83.27	
Runoff Percent	----	0.6	2.4	0.6	2.9	0.7	2.4	1.8	4.2	
RO Curve Number	----	69.4	73.4	57.8	73.5	59.7	63.7	58.1	62.3	
Peak Flow	Ft <sup>3</sup> /Sec	0.32	1.45	0.74	2.75	0.49	1.33	1.02	6.01	
Peak Flow	10 <sup>-3</sup> In/Hr	1.50	6.62	3.36	12.58	2.22	6.08	4.66	27.48	
Rational Coeff.	----	0.0047	0.0207	0.0071	0.0267	0.0072	0.0197	0.0057	0.0335	
Initial Conditions:										
Soil Moisture	Inches	4.45	5.00	4.96	5.00	4.95	5.00	4.11	5.00	
Streamflow	Ft <sup>3</sup> /Sec	0.0044	0	0.0350	0	0.0131	0	0.0219	0	
Calibration Data:										
(ΣΔ <sup>2</sup> /N) <sup>1/2</sup>	10 <sup>-3</sup> In.	0.070	---	0.090	---	0.190	---	0.150	---	
R <sup>2</sup>	----	0.919	---	0.977	---	0.856	---	0.926	---	
Data Points (N)	No.	37	---	39	---	62	---	37	---	

NOTE: \* For 1/2 Hr duration.

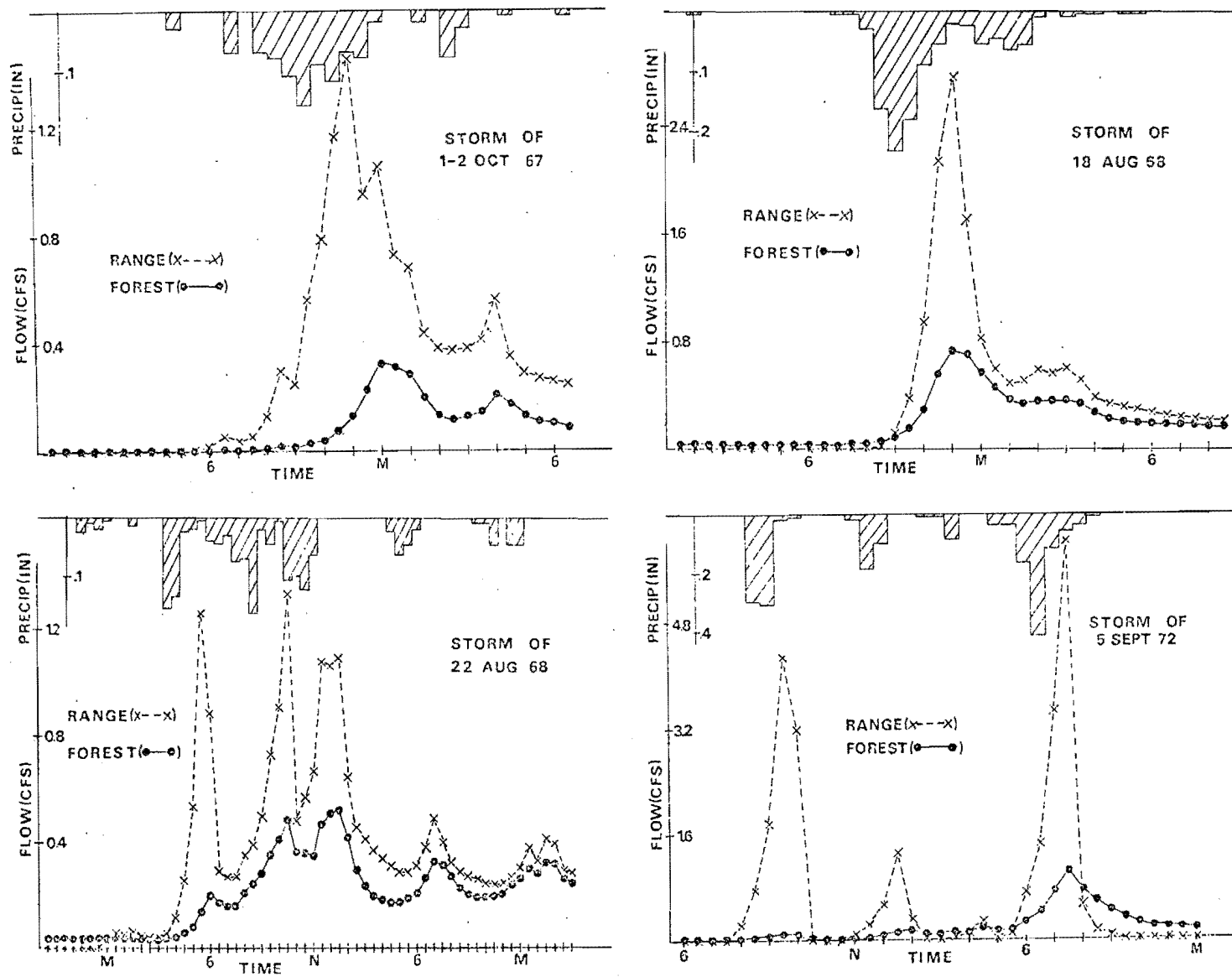


Figure 9. Storm reactions on a forested watershed as represented by the West Branch of Chicken Creek, and for a hypothetical "range land" watershed, simulated by adjustment of parameters.

Thus, questions arise about the modeling process itself, many of which will be answered only through additional research which is directed to finding specific answers. Some of these questions are stated as follows:

1. To what degree are present techniques able to represent the inner workings of a "real world" system?
2. To what extent can a "good fit" be obtained by judicious parameter selection and identification without regard to the model structure in terms of the real system?
3. Is it possible to reproduce system output (to a tolerable degree of accuracy) with incorrect representation of system processes?
4. Are modeling techniques more sophisticated than justified by the data usually available for model calibration and operation? A reasonable guideline is to use the simplest model possible within the constraints imposed by available data and the kinds of questions which the model will be used to solve.
5. How important to the model predictions are accurate and high resolution data?
6. How important is the problem of multiple solutions to parameter identification?
7. Does parameter selection and identification represent a compromise of basic theory in model development?
8. What objective functions lead to the most dependable and accurate results in parameter identification?
9. What hazards and problems are introduced by the fact that the user is often not aware of the assumptions incorporated into the model and upon which the predictions depend?
10. Is modeling worthwhile, or are we merely playing mathematical games with ourselves?
11. Is modeling an exercise in "academics"? In other words, is modeling a more advanced technique than we are able to effectively utilize at present? In many respects we seem not yet able (or unwilling) to use and implement even the gross answers based mainly on experienced judgment.

#### SUMMARY

The question might be asked: "What are the alternatives to the application of simulation modeling techniques?" Possible answers to this question are as follows:

1. Apply trial and error methods.

2. Exercise sound judgment in reaching solution.

3. Further develop high resolution models which are based on very small (differential) increments in the space and time dimensions.

Many of our current modeling techniques may be regarded as purely "black box" in nature. The general and more sophisticated simulation models are based somewhat on fundamental relationships, and thus might be viewed as being "gray boxes" or even "white boxes" (Crawford, 1970). Some progress is being made in moving further in the direction of increased definition and representation of the fundamental system processes. Computer models are certainly not "magic words" and the user needs to beware of expecting too much of them. Even the application of judgment, which is the translation of background experiences to the problem at hand, is in a broad sense a form of modeling, so perhaps we are involved in a question of semantics. Modeling is still (to a large degree) the sophisticated application of sound judgment. Shih and others (1972) refer to computer modeling as "the finest product of the hydrologist's art." Thus, perhaps the best that we can do is to use the basic tools which are at hand, while at the same time recognize their current limitations and strive for improvement in terms of specific needs as they arise.

#### ACKNOWLEDGMENTS

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## **Session III**

# **Watershed Management: State of the Practice**



# Vegetation Manipulation — A Case Study of the Pinyon-Juniper Type

Gerald F. Gifford\*

The general topic of vegetation manipulation and its impact on the many interrelated aspects of wildland hydrology is a broad one, especially in light of the many vegetation types which together comprise the rangeland resource in the United States. Since space and time are both somewhat limited, I would like to approach the problem by using one detailed example of a common vegetation manipulation practice used throughout Nevada, Utah, Colorado, Arizona, and New Mexico—that of converting pinyon-juniper (*Pinus* spp.-*Juniperus* spp.) woodland to either a grass or grass-shrub combination. We will look at this type in some detail, and then assume that our findings, to the extent possible, are applicable to other vegetation types. Principles and concerns derived from looking at the pinyon-juniper type will undoubtedly be very similar to those which are found elsewhere in other U.S. rangeland plant communities where vegetation manipulation is a possibility.

## PINYON-JUNIPER MANIPULATION PRACTICES

Sites selected for removal of pinyon-juniper are generally characterized by relatively gentle slopes (less than 30 percent), degraded range condition, adequate soils (at least 60 centimeters of profile above bedrock), and a fairly dense stand of trees. Various techniques have been used for eliminating the trees—individual tree dozing, hand felling of individual trees, burning, spraying with herbicide, gouged out and mashed with hugh U.S. Army war surplus rigs (Big Jack), and chaining. Of these techniques, chaining is the most common and involves dragging a large anchor chain (27-40 kilograms per link) between two tractors to uproot the trees.

Grass and browse seed are usually drilled or broadcast seeded, depending on debris disposal techniques. If the debris is pushed into windrows or piles, then drill seeding following piling is the common practice. If the debris is left scattered about the landscape, then broadcast seeding during some phase of the operation is standard procedure.

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Now looking only at the conversion practice, let's analyze what has happened from the standpoint of site disturbance and what might be ascertained based on simply an ocular survey of the respective site and a simplistic understanding of watershed hydrology. Table 1 provides a simple qualitative measure of probable observed watershed impacts. Absolute magnitudes are not given.

## CONCEPT

*From a watershed standpoint, different treatments for eliminating pinyon and juniper trees will have varying impacts on easily observed watershed characteristics. These impacts may influence total hydrology of the area.*

Obviously the above information would provide few guidelines for the land manager toward evaluating the total worth of a manipulation practice from a watershed standpoint. However, unfortunately, even less information than this has been used in expressing the hydrologic benefits or, conversely, detrimental aspects of various range improvement practices.

## WHAT DO WE KNOW ABOUT HYDROLOGY OF THE PINYON-JUNIPER TYPE? — A BRIEF REVIEW

### Interception

Two studies have been published regarding direct measures of interception losses within the pinyon-juniper type (both in Arizona). The first study, reported by Skau (1964), covered both Utah and alligator juniper on the Beaver Creek watershed. He found that throughfall could be predicted with reasonable accuracy for either species by a single equation. Stem flow accounted for only 1 to 2 percent of the total precipitation. Average interception in the Utah juniper type during a single year of measurement was about 17.2 percent of the average annual precipitation for that year.

In the second study, reported by Collings (1966), statistical analyses indicated no significant difference

between juniper and pinyon throughfalls; one curve may best be used to describe the precipitation-throughfall relation for both tree types.

#### Interception summary

1. Based on data from a one-year study, precipitation-interception relations apparently are reasonably similar for both Utah and alligator juniper.

2. Based on data from a three-month study (July to September), an equation is available for estimating interception in a mixed pinyon-juniper stand.

#### Infiltration

Studies of the infiltration process on pinyon-juniper rangelands have been reported from New Mexico, Nevada, and Utah. In New Mexico, Smith and Leopold (1942) found mean infiltration rates for wet runs (soils at field capacity to start) on 39 woodland plots averaged 3.2 cm/hr.

Blackburn and Skau (1974) looked at infiltration rates in several pinyon-juniper communities in Nevada. Their data indicate that 30-minute infiltration rates in plant communities on gentle slopes (less than 13 percent in this study) in which species of pinyon and/or juniper may be present may average 6.3 cm/hr when soils are initially dry and 5.3 cm/hr when soils are initially at field capacity. Based on data from two sites, there was no indication that chaining (either double or single) was detrimental to infiltration capacities.

Studies in Utah (Williams, Gifford, and Coltharp, 1969; Gifford, Williams, and Coltharp, 1970; Williams, Gifford, and Coltharp, 1972; Loope and Gifford, 1972; Buckhouse, 1975) have shown that infiltration and erosion rates at a given point on chained sites have not been particularly affected by the treatment practices. If there has been any influence, then the chaining impact would be

expected on sites where debris has been windrowed, and the impact would probably be slightly negative.

Near Blanding, in southeastern Utah, part of the reduction in infiltration rates on a windrowed treatment could be attributed to destruction of cryptogamic soil crusts (Loope and Gifford, 1972). However, the reduction apparently is not a permanent one since total protection (no grazing by domestic livestock) of the same windrowed site for a period of 6 years allowed sufficient time for recovery of infiltration rates (but not the cryptogamic cover) (Buckhouse, 1975).

#### Site factors influencing infiltration

Williams, Gifford, and Coltharp (1972) indicated that total porosity in the 0-7.5 cm layer of soil, percent bare soil surface, soil texture in the 0-7.5 cm layer of soil, and crown cover (percent or kg/ha) were all important in predicting infiltration rates on sites in Utah. However, the importance of any one variable varied with time since beginning of rainfall and also with geographic location.

Results presented by Blackburn (1973) in Nevada are similar in that the importance of measured site factors in predicting infiltration rates at a point varied from one watershed to another. In general the rate at which water entered the soil profile was governed mainly by the extent and soil surface horizon morphology of interspace areas between zones of accumulation of litter and soil under plants.

#### Influence of grazing on infiltration

Vegetation manipulation practices do not stop at that point, but they also include secondary management activities, of which grazing by domestic livestock and big game are probably most important. Studies by Busby (unpublished data) and Buckhouse (1975) represent the only efforts at trying to isolate the grazing impact on

**Table 1. Probable watershed impacts associated with various techniques of tree removal within the pinyon-juniper type.**

Treatment	Probable Watershed Impact <sup>a</sup>			
	Interception	Surface Soil Mechanical Disturbance	Bare Soil (%)	Increased Detention-Retention Storage on Soil Surface
Pinyon-juniper woodland, untreated	None	None	None	None
Hand-felling of individual trees, debris left in place	+	None	None to -	+
Individual tree dozing, debris left in place	+	-	-	+
Burning	+	None	-	-
Herbicide	+	None	-	None
Chaining, debris in place	None to +	-	-	+
Chaining, debris windrowed	+	-	-	-
"Big Jack"	None to +	-	+	+

<sup>a</sup>+ = a probable positive benefit, magnitude undefined.

- = a probable negative benefit, magnitude undefined.

watershed values on pinyon-juniper sites. Working in southeastern Utah on sandy-loam soils, Busby found that instantaneous removal of vegetation (through clipping) does not immediately influence microhydrologic systems within the type. The same was true using one-time compaction intensities of 0, 30 percent and 60 percent on plots in ungrazed exclosures. The compaction force, 13.6 kg/cm<sup>2</sup>, favored the static or standing load exerted by mature cattle, though two to four times this load may occur when the animal moves. Although the clipping and artificial trampling did not affect infiltration rates, grazing by cattle did. Apparently the impact of grazing is not immediate, but rather is accumulative throughout both seasons and years. Even one season of grazing will produce changes (Buckhouse, 1975), and protection of up to four years may be needed on even sandy-loam soils to fully regain maximum infiltration capacities (Busby, unpublished data).

#### *Influence of burning on infiltration*

Buckhouse (1975) has briefly looked at the influence of burning pinyon-juniper debris on infiltration rates on sandy-loam soils in southeastern Utah. He found that burning a debris-in-place site depressed infiltration rates during select intervals of a simulated storm, the possible reason being formation of nonwettable soils. This aspect needs to be examined in much greater detail.

#### *Infiltration summary*

1. Studies completed to date indicate that infiltration rates have only been slightly affected when comparing chained sites to the undisturbed woodland. Coarse-textured soils probably account for much of this. If there is a decrease in infiltration rates due to chaining activities, then the decrease will probably occur on chained-with-windrowing treatments, this being the result of rather severe mechanical disturbance of surface soils during the windrowing process. The mechanical disturbance may actually increase permeability of surface soils (Gifford and Tew, 1969), but infiltration at the soil-air interface is decreased.

2. Because of the variability in pinyon-juniper site characteristics, it is difficult to pinpoint exactly those factors that consistently influence infiltration rates.

3. The impact of grazing on infiltration rates appears accumulative (up to some undefined point), and effects of even a single grazing season can be detected. Complete protection for four years of a grazed site on sandy loam soils restored infiltration capacities to a maximum.

4. Burning of debris appears to depress infiltration rates.

#### **Soil Moisture Patterns**

Skau (1964) found in Arizona that clearing alligator juniper and Utah juniper on the Beaver Creek watershed

had little effect on water yields as influenced by soil moisture storage in the upper 60 cm of the soil profile.

Gifford and Shaw (1973) analyzed data for two and three years of sampling from chained pinyon-juniper sites in southwestern and southeastern Utah, respectively. Soil moisture patterns were studied under chaining-with-windrowing, chaining with debris-in-place, and natural woodland. Results of the study indicate the greatest moisture accumulation occurred under debris-in-place treatments (as compared to woodland controls), during the first six months of each year at Milford and regardless of season at Blanding. The woodland had the least soil moisture throughout most of each year. Most moisture flux took place in the upper 60- to 90-cm of soil profile, with only minor changes occurring at greater depths. Differences in soil moisture patterns were attributed to changes in microclimates due to chaining, different rooting depths and length of growing season, mulching effect of litter on the debris-in-place treatment, and possible differences in snow accumulation. There was no evidence of deep seepage on any chaining treatment at either site. Lack of any deep seepage has also been noted by Myrick (1971) in Arizona on the Cibecue Ridge Project.

#### **Runoff**

Based on results of infiltrometer studies previously discussed, it might appear that vegetation manipulation practices (at least where chaining is involved) would have little influence on runoff. This generalization must be modified, however, depending on debris disposal techniques and also where there is sufficient winter snowfall and rainfall to generate winter streamflow. Studies outlined by Myrick (1971) at Cibecue Ridge indicate that chaining and burning of slash, followed by seeding, will cause an increase in runoff for the first couple of years following treatment, then runoff decreases as the new plants establish themselves. He indicates that size of storm may be an important factor in such evaluations. From the Beaver Creek watershed studies, the only significant response in annual streamflow has been from a watershed sprayed with the herbicide Picloram (Clary et al., 1974). Though a 14 percent increase in water yield over a 7-year period has been noted for a watershed on which trees were felled (no burning, regrowth restricted), it was not significant. Baker et al. (1971) report the results of a large storm which occurred during September of 1970 on the Beaver Creek site. Total precipitation for this 24-hour storm period ranged from 9.9 to 12.4 cm on the six pinyon-juniper watersheds (25-year storm or larger). In the Utah juniper type, the cabled and chemically treated watersheds had 2.0 and 1.3 times, respectively, greater peak discharges than their woodland controls. The response of total runoff on the cabled and chemically treated watersheds was 2.1 and 1.3 times their respective woodland controls. There was no effect from a 5-year old treatment where the trees were felled and left in place. Where only select portions of the watershed have been

treated, increased runoff may not be noticeable (Collings and Myrick, 1966).

In Utah, Gifford (1973) found during a five-year study that runoff from .04-hectare runoff plots on chained-with-windrowing sites yield from 1.2 to 5 times more water during a runoff event than respective woodland plots. Runoff from debris-in-place plots was equal to or less than that measured from the natural woodland for all storms. On these particular sites (perhaps 250 mm annual precipitation) all runoff results from high intensity convectional thunderstorms during the period from about June 15 to September 15 of each year. Results from this study indicate strongly that debris-disposal techniques are the key to minimizing runoff from chained pinyon-juniper sites. Since infiltration rates are only slightly affected by the chaining activities (at least on sites in Utah and perhaps also in Nevada), then the runoff differences are obviously the result of debris and depressions left from uprooting trees which simply hold water on site until it has the opportunity to infiltrate the soil. Skau (1961) has estimated that the volume of pits alone (left after uprooting juniper trees) on the Beaver Creek watershed was enough to reduce surface flow 0.2 to 0.7 cm annually. That did not include influence of debris which was left scattered around.

#### *Runoff summary*

1. Given a runoff event due to high intensity rainfall, least runoff may be expected from sites chained with debris-left-in-place, followed very closely by the natural woodland and also sites which have simply been sprayed to kill the trees. Greatest runoff will occur on sites chained with debris windrowed.

2. Where water yield is important, spraying (but no tree removal) is most effective in the Utah juniper type. At higher elevations in Arizona where alligator juniper is found, tree removal may result in a slight increase in water yield. Where only select areas of a watershed are treated or where tree densities are low, increases in water yield should not be expected.

#### **Water Budgets**

Even though it is readily evident that evapotranspiration approximates precipitation on many pinyon-juniper sites, the only published attempt at deriving approximate annual water budgets is that of Gifford (1975) for two sites in southern Utah. Figures indicate that most of the 250 mm of annual precipitation falling on each treatment is lost through evapotranspiration, with much of the balance being lost through interception.

#### **Water Quality**

Sediment is the most important water quality parameter associated with pinyon-juniper sites. Studies of 28 chained sites throughout central and southern Utah

have shown that point measures of sediment production potentials are, for the most part, not increased by chaining activities (Williams, Gifford, and Coltharp, 1969; Gifford, Williams, and Coltharp, 1970). Based on a smaller sample, the same appears true in Nevada (Blackburn, 1973). These results hold true for entire watersheds on the Beaver Creek study where the conclusion, after 13 years of record is that there appears to be no meaningful change in sediment yield after either cabling or applying herbicide to the pinyon-juniper type (Clary et al., 1974). Data from .04-hectare runoff plots in Utah are in agreement with the above with regards to debris-in-place treatments, but on debris-windrowed treatments, when runoff exceeds about 0.1 cm from the unchained woodland, from 1.6 to 6 times more sediment can be expected from the windrowed areas than from the adjacent woodland (Gifford, 1973). This once again shows the hydrologic importance of scattered debris on the landscape.

#### *Factors influencing erosion*

Factors influencing erosion on pinyon-juniper sites have only been identified in a general way. Though numerous sites have been studied (Williams, Gifford, and Coltharp, 1972; Blackburn, 1973), factors that influence potential point sediment discharges are so variable from one geographic location to another that no consistent relation has been found. Sediment data from small watersheds or large runoff plots indicate that minimizing surface soil disturbance and leaving debris in place are both important in keeping sediment yields to a minimum on manipulated sites.

#### *Other water quality parameters*

Some limited data on chemical and/or biological properties of runoff water from pinyon-juniper watersheds are available from the Beaver Creek study (Clary, 1974) and also from small plot studies conducted by Buckhouse (1975) in southeastern Utah. Data from the Beaver Creek study are minimal, but they indicate that water produced from the juniper watersheds generally exceed minimum quality standards for irrigation, public water supply, and for aquatic life. Picloram, the herbicide used on watershed 3 in 1968, was slightly mobile in that about 1.3 percent left the watershed in runoff. Of this, 90 percent left within the first 7 months after treatment, during which 33.5 cm of precipitation fell and about 17,270 m<sup>3</sup> (14 acre-ft.) of water had run off the treated watershed.

Buckhouse (1975) has indicated that in southeastern Utah potential public health hazards of livestock grazing on semiarid open range on gentle slopes are minimal. As for nutrient release following burning, season-long, significantly increased amounts of phosphorus and potassium were measured in overland flow from simulated rainfall following burning in a chained with debris-left-in-place site. No significant changes were detected in calcium, sodium, or nitrate-nitrogen contents in the runoff due to differences in land treatment.

*Water quality summary*

1. Indications are that sediment discharges have not increased on pinyon-juniper sites due to vegetation manipulation practices. An exception to this is the increased quantity of sediment produced from debris-windrowed sites during high intensity thunderstorms in Utah.

2. Factors influencing sediment yields at given points on a pinyon-juniper site are variable from site to site. Minimum sediment yields (equal to that from undisturbed woodland) may be expected where surface soil disturbance is minimized (as with spraying a herbicide) or where debris is left in place on a chaining project.

3. Chemical aspects of water from pinyon-juniper sites indicate good-quality water suitable for irrigation, public water supply, and for aquatic life.

4. Potential public health hazards of livestock-grazing on semiarid open range on gentle slopes appear to be minimal.

5. Given a runoff event, runoff during the first year from burned debris-in-place sites may contain increased amounts of phosphorus and potassium, but not calcium, sodium, or nitrate nitrogen.

**CONCEPT**

*Range improvement practices are not all beneficial from the standpoint of runoff and sediment production. Examples include chaining pinyon-juniper, plowing, grazing management improper burning practices, and examples involving poor construction practices. In fact, most research has shown that improvement practices which involve severe mechanical disturbance should not be expected to improve hydrologic conditions. Exceptions to this of course would be those improvement practices which result in significant volumes of retention and/or detention storage on the soil surface. Since the life of most mechanical treatment is relatively short, it is imperative that desirable vegetation cover be established and properly maintained. Where adequate [ 70 percent cover] vegetation has been established as a result of some improvement scheme, then improvements in hydrologic behavior are also generally noted [assuming a degraded condition to start]. However, where the potential for a 70 percent plant cover does not exist, then reductions in runoff or sediment cannot be expected from most improvement practices. Where furrows, etc. are constructed, reduction will result so long as retention and detention surface storage volumes are not exceeded.*

**WATER USE EFFICIENCIES OF NATIVE vs  
SEEDED SPECIES—SOMETHING TO  
CONSIDER?**

The quantity of water a plant requires for the production of a gram of dry matter, exclusive of roots, has

been termed by Briggs and Shantz (1913, 1914) as its water requirement. Although it is recognized that many factors influence water requirements of plants (available water, nutrient availability, genotypic variation, environmental demands, stage of growth, rooting depth, length of growing season, soil temperature, etc.), it would appear logical that water requirement per unit of plant growth would be at least one of the several considerations in ultimately deciding among several species which might be seeded on a given site. Within the pinyon-juniper type a number of species of both grasses and shrubs have been used on seeding projects, though crested wheatgrass (*Agropyron cristatum*) has been most popular. Though selection of seeded species has actually (in real life) been made on the basis of things other than water requirements, water requirements should be examined to ascertain if differences do exist and, if so, the relative magnitudes of those differences. (See table on following page.)

The very brief list on page 156 indicates significant variability with a species, but a general trend of higher water-use efficiencies may be noted for the grasses as compared to the shrub species (last three on the list). McGinnies and Arnold (1939) and Dwyer and DeGarmo (1970) have also called attention to this fact. However, in conclusion, this type of information does not appear to lend itself as a worthwhile guideline for selecting species useful in seeding.

**OTHER CONSIDERATIONS WITHIN THE TYPE****Impacts on Forage Production**

Dwyer (1975) has recently reviewed the response of livestock forage to manipulation of the pinyon-juniper ecosystem. In general, the pinyon-juniper type is well suited to grazing cattle and sheep, and it appears that the type must be viewed for the future as a place where forage supply for domestic and wild animals can be increased. In fact, increased forage production was the primary justification for most of the early pinyon-juniper conversion projects in the southwest. Dwyer, however, summarizes his review with the following statements:

All in all, I was surprised at how little factual information is available regarding the relationship between forage production and pinyon-juniper trees. It seems that deductive reasoning has played a role in many pinyon-juniper manipulation projects. That is, it appears quite logical to assume that when trees are removed, forage will increase. It is limited, but the data do not always support this reasoning. There are simply too many interacting ecosystem factors at work. It is reasonable to say that, generally, the deduction is sound.

**Impacts on Mule Deer (*Odocoileus hemionus*) and Other Wildlife**

In a total multiple-use evaluation of vegetation manipulation practices, wildlife habitat must definitely be

Water Requirements of Native or Seeded Species  
Within the Pinyon-Juniper Type  
(g water/g dry weight)

<i>Agropyron cristatum</i> or <i>Agropyron desertorum</i> or <i>A. cristatum</i> x <i>A. desertorum</i>	573-616 (Bleak & Keller, 1973)	705 (Shantz & Piemeisel, 1927)	880-1,024 (Dillman, 1931)
<i>A. sibiricum</i>	549-612 (Bleak and Keller, 1973)		
<i>Elymus junceus</i>	598 (Bleak and Keller, 1973)		
<i>Agropyron intermedium</i>	126-180 (Baker & Hunt, 1961)		
<i>Agropyron smithii</i>	429-701 (Bailey, 1940)	1076 (Shantz & Piemeisel, 1927)	1,247-1,420 (Dillman, 1931)
<i>Bouteloua gracilis</i>	596 (McGinnies & Arnold, 1939)		
<i>Bouteloua eriopoda</i>	572 (McGinnies & Arnold, 1939)	836-1,141 (Dwyer & DeGarmo, 1970)	
<i>Hilaria mutica</i>	916-1,127 (Dwyer & DeGarmo, 1970)		
<i>Salsola kali</i>	98-222 (Dwyer & Wolde-Yohannis, 1972)	107-263 (Wallace, 1970)	
<i>Atriplex canescens</i>	1,544-1,946 (Dwyer & DeGarmo, 1970)		
<i>Ephedra</i> spp.	1,946 (McGinnies & Arnold, 1939)		
<i>Gutierrezia sarothrae</i>	2,578-5,954 (Dwyer & DeGarmo, 1970)		

included. Terrel and Spillett (1975) in a recent review have found that conversion of pinyon-juniper ranges, as currently practiced, is a "mixed blessing" for mule deer, with each site being somewhat unique. Conversion practices generally increase the supply of succulent spring forage; however, winter forage from woody vegetation is perhaps the major value of the pinyon-juniper type. They also state that the success of conversion programs in increasing deer winter range quality is uncertain, with the variation in conversion impact appearing to be partly a function of the intensity of the conversion relative to deer density and also total size of the winter range. In summary, Terrel and Spillett give the following:

The proper concept in P-J management for deer on winter ranges is to "punch" strategically spaced holes in the P-J, not to leave islands of P-J in chained units. The most preferred, but expensive, treatment of P-J ranges in poor condition would be to spot thin mature trees to a crown cover of perhaps 15 percent and a density of 50 per acre. The interspaces then should be seeded to native grasses and shrubs. This would provide the optimum habitat composition of protective cover, winter browse, and spring succulents for deer. . .

Little or nothing is known about most of the other vertebrate species (birds, mammals, reptiles, fish and amphibians) that are found within the pinyon-juniper type.

### Impacts on Archeological Values

Though the pinyon-juniper type contains many archeological resources, information regarding the impact of vegetation manipulation practices on those resources is almost entirely lacking. A single paper, by DeBloois et al., indicates that damage to archeological materials from pinyon-juniper chaining (other treatments not evaluated) can be summarized thusly: major damage takes two forms, displacement and concealment are the major impact in areas of tractor travel and tree uprooting. Breakage occurred only in areas of tractor travel. This study has hampered by the very small numbers of samples taken.

### Economic Considerations

Guidelines for benefit-cost analyses which are adequate for current decision making needs have recently been outlined by Workman and Kienast (1975). In addition, three recent benefit-cost analyses of pinyon-juniper conversions were reviewed and the cost and benefit categories treated in these three studies were contrasted with those proposed as essential for pinyon-juniper management decisions. Workman and Kienast comment as follows:

In summary, the benefit-cost ratios in excess of 1.00:1 which were reported by all three recent studies of pinyon-juniper conversions are

not, by themselves, sufficient justification for this practice. Neither are benefit-cost ratios of less than 1 sufficient grounds for abandonment of proposed P-J conversion projects. Our plea is for site specific analysis of each of the items in Table 2 for any P-J conversion project which may be proposed in the future. Such an analysis will necessarily require more citizen input and a more active effort on the part of land management agencies to determine how the public wants public lands to be managed.

**Table 2. Cost and benefit categories required for benefit-cost analysis of P-J conversion (from Workman and Kienast, 1975).**

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I. Costs
A. Quantifiable
1. Market priced
a. Pre-treatment
b. Treatment
c. Post-treatment
d. Foregone benefits
2. Non-market priced
a. Physical
b. Biological
B. Non-quantifiable
1. Aesthetics
2. Recreation
3. Archeologic
II. Quantifiable
A. Quantifiable
1. Market priced
a. Livestock forage
b. Woodland products
2. Non-market priced
a. Biological
b. Physical
B. Non-quantifiable
1. Aesthetics
2. Recreation

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# Interactions Between Vegetation and Stream Water Quality in Australia

A. J. Peck\*

## INTRODUCTION

For some 50 years it has been hypothesized that the annual crops and pastures on unirrigated farmland across southern Australia use less water than the evergreen native vegetation which they have replaced. This hydrologic disturbance has brought about accelerated leaching of solutes from soils and relatively inactive groundwater systems, which in turn causes salinization of soil in newly developed seepage areas, and increased salinity of streams.

About 200,000 ha of previously productive unirrigated soil in Australia is now so saline that the usual crops and pastures will not grow. Presumably there is a reduced yield due to non-lethal salt levels over a large area too. But this is not considered to be a major agricultural problem in Australia since it affects only about 1 percent of the farmed land in the regions where it occurs. However, there is a growing awareness that increasing salinity is reducing the already sparse amounts of good quality stream water in many parts of southern Australia.

This paper discusses the processes involved in the development of saline seepages in Australia, a method for estimating the effect of vegetation changes on stream salinity, and a watershed vegetation strategy designed to minimize salt seepage into streams. Attention is focused on south-western Australia where the problem is most intense, but similar situations exist in the States of South Australia, Victoria, and New South Wales.

## THE AREA CONSIDERED

Figure 1 locates the area which is loosely referred to as the Darling Range. Soils and land forms typical of the area have been described by Mulcahy (1967) and Bettenay and Mulcahy (1972). It is generally a gently undulating landscape of lateritic soils ranging in elevation between about 250 and 300 m above sea level. For hydrologic purposes the essential feature is that a relatively coarse

and permeable surface soil of variable depth (up to 6 m) generally overlies a much less permeable kaolinitic subsoil. In many parts of the area the soils have developed *in situ* weathering of granitic gneiss and dolerite dykes which form the basement rock at an average depth of 20 m (Dimmock et al., 1974).

The climate is Mediterranean. Yearly rainfall ranges from 500 to 1300 mm with about 70 percent of this falling in the winter months of May to September when rain exceeds estimated tank evaporation (Australian Water Resources Council, 1968). See Figure 2. Winter temperatures are mild (about 10°C) and snow is rare, while summers are warm (about 20°C) and dry. The original vegetation was a dry sclerophyll forest dominated by species of *Eucalyptus*. Soil cores reveal roots which penetrate to the depth of the permanent water table where one exists within the weathered mantle, or to basement rock.

The natural forest provides timber, water, habitat for animals, and recreation for man. However, this forest is being steadily cleared for farming, strip mining (bauxite), roads and power lines, and plantation forestry. Other areas of the natural forest are changing due to a root fungus (*Phytophthora cinnamomi*) which generally kills the most common and valuable timber species *Eucalyptus marginata*.

After mining, or severe attack by *Phytophthora*, exotic evergreen trees are planted. In farm development the deep-rooted evergreen native plants are permanently replaced by winter-growing annual pasture and crop varieties.

## SOLUTE CYCLING AND COMPOSITION

Outputs of chloride ( $\text{Cl}^-$ ) in the streamflow from several large catchments in the Darling Range area have been compared with estimated inputs of  $\text{Cl}^-$  in rainfall (Peck and Hurlé, 1973). There appears to be a relatively small net loss of  $\text{Cl}^-$  from forested areas, and a very much larger loss from farmed catchments. The area is notable for the relatively large input of  $\text{Cl}^-$  in rainfall which ranges from 20 to 130  $\text{kg ha}^{-1} \text{yr}^{-1}$ .

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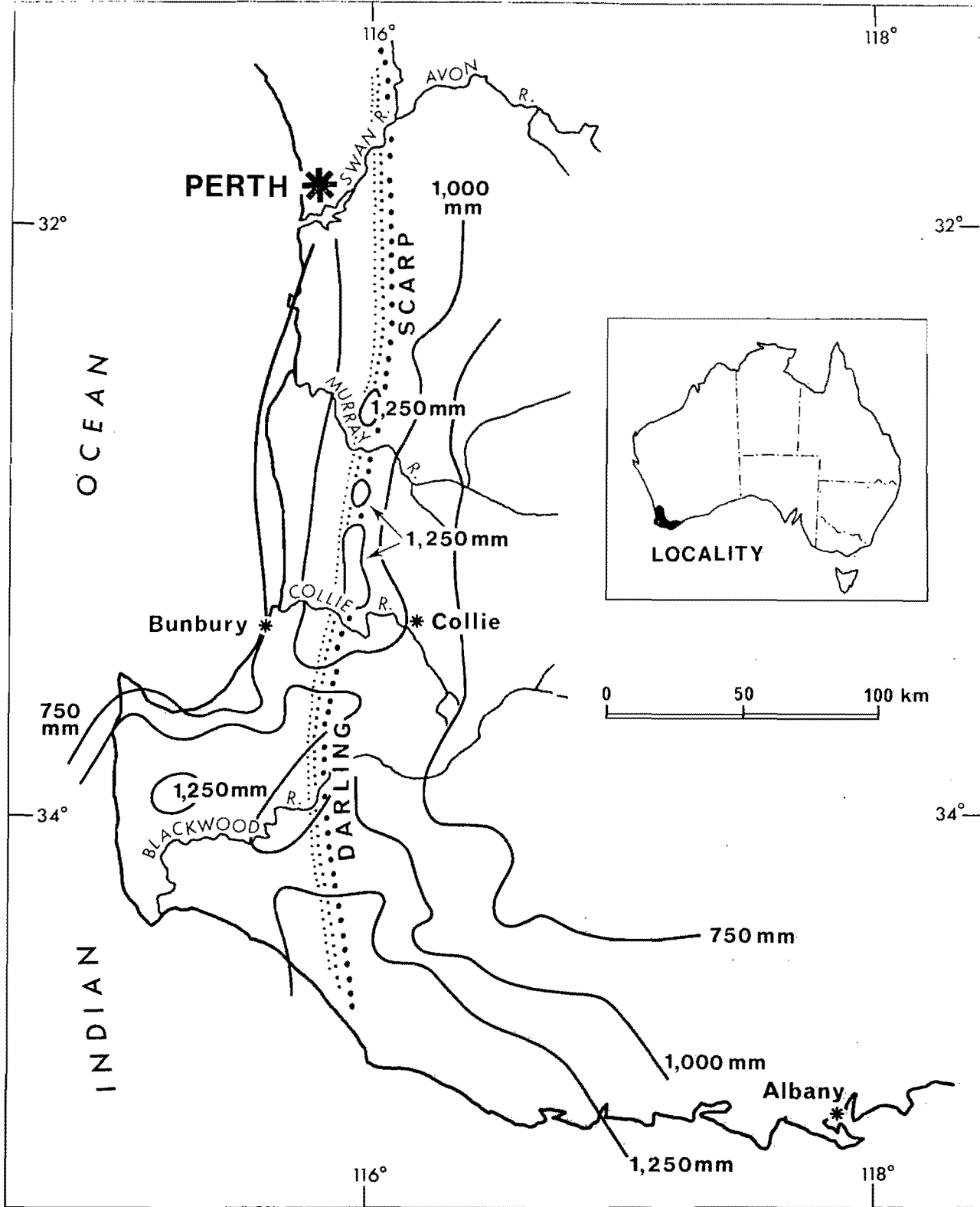


Figure 1. Location of the area and average yearly rainfall.

More recent work on much smaller experimental catchments has not always supported the earlier results on Cl<sup>-</sup> balances. The output of Cl<sup>-</sup> in the ephemeral streamflow from some forest land is of order 1 percent of the input in rain. It is likely that underflow of water is an important factor in the transport of solute from these small, upland catchments where the stream is not incised to basement rock. However, the alternative possibility, that the undisturbed catchments are accumulating solutes under the present climate regime, cannot be discounted.

Total salt storage in the soil profile has been estimated by Dimmock et al. (1974) to range from order 10<sup>5</sup>kg ha<sup>-1</sup> in higher rainfall regions to order 10<sup>6</sup>kg ha<sup>-1</sup> in lower rainfall regions of the Darling Range. Soil solute concentrations are as high as 30,000 mg/L. It is uncertain how the natural vegetation has adapted to this belowground environment. Figure 3 shows a typical soil solution concentration profile. This is very closely followed by the Cl<sup>-</sup> distribution.

The peak of solute concentration at intermediate depth, which is evident in the profiles in Figure 3, is very frequently encountered. This peak may be associated with the pattern of water uptake by roots of the natural vegetation, soil morphology, etc. Further work is underway to develop a better understanding of the interactions between vegetation and the distribution of solute in the soil profile.

The spatial distribution of groundwater salinity has been determined from observation bores at 200 m intervals in a 94 ha catchment. The bores with relatively high salinity groundwater are located in a band, which suggests some geological influence, but this is not at all apparent from other data or observations.

With few exceptions the ionic composition of groundwaters in the Darling Range area is very similar to that of seawater (Hingston, personal communication,

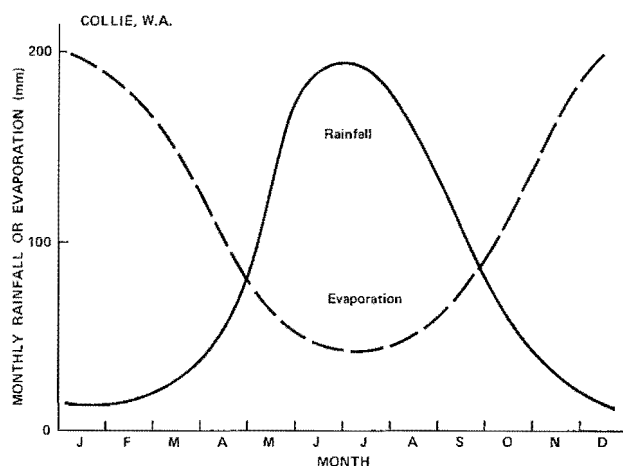


Figure 2. Seasonal variations of rainfall and estimated tank evaporation at Collie, Western Australia.

1974). This confirms the implication of the Cl<sup>-</sup> balance data that atmospheric deposition is the major source of solute in the soil-water system. Further support for this theory is provided by the estimated accumulation time (salt storage divided by yearly salt deposition) of order 10<sup>4</sup> yr which is small in comparison with the geologic time scale of this landscape (Dimmock et al., 1974).

### WATER BALANCES

The monthly water budget of a small (19 ha) experimental catchment under native vegetation is shown in Table 1.

Most of the winter rainfall enters the soil with very little surface runoff. Considering the uncertainty in their determination, the winter evaporation rates are close to those estimated for an evaporation tank. In the spring, the actual evaporation rate increases due to an increasing demand, but when the soil moisture store is depleted the actual rate falls off to a minimum in late summer. The actual evaporation rate in summer may be underestimated due to water uptake from depths greater than that of the neutron access tubes.

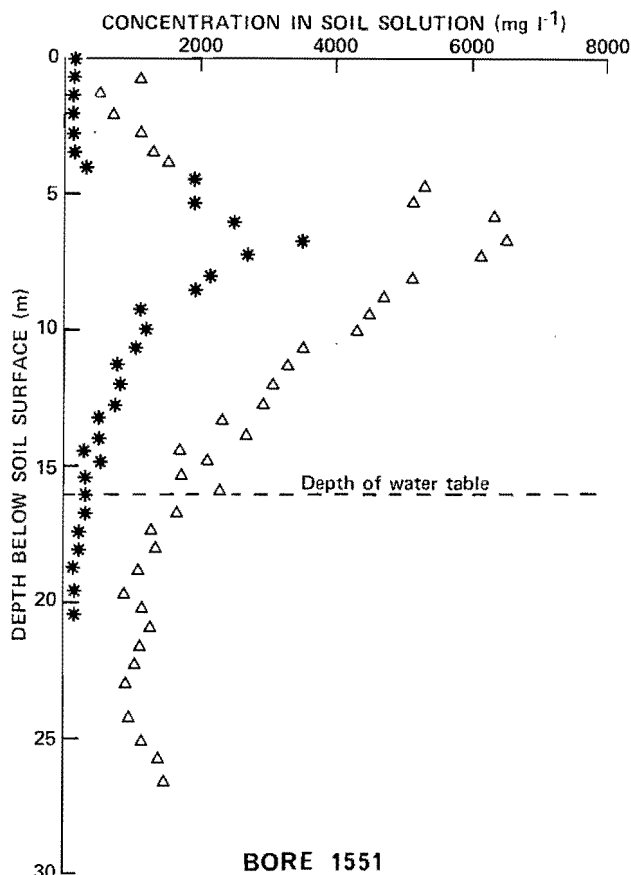


Figure 3. Typical variation of Cl<sup>-</sup> concentration and salinity (Total Dissolved Solids concentration) of soil water with depth in soils of the Darling Range area.

Streamflow in the region is generally ephemeral due to the yearly patterns of rainfall and potential evaporation. The permanent water table in lower rainfall forested areas is often well below the soil surface, but a lateral flow of water develops during winter in parts of the more permeable surface soil. This is in the form of a perched water table on the less permeable kaolinitic layer. These perched water tables discharge into streams. The permanent water table intersects the soil surface in higher rainfall catchments, except in summer when transpiration can match the rate of groundwater movement.

It has been estimated that, in general, the crop and pasture species on farmed land use between 23 and 65 mm yr<sup>-1</sup> less water than the original forest vegetation (Peck and Hurle, 1973). A similar difference in water use between forest and grasslands has been estimated in South Australia (Holmes and Colville, 1968).

Primary factors contributing to the lesser use of water by pasture than by forest are depth of rooting (more than 20 m for forest in the Darling Range against 1 or 2 m for crops and pastures on the same land), and the length of the period of transpiration (throughout the year for forest against roughly May to November for crops and pastures). Other factors which could also contribute are differences in rainfall interception, albedo, and aerodynamic roughness.

Figure 4 shows some typical soil moisture profiles at a forested site. Clearly water penetrates in winter to a depth of more than 6 m. Since annual crops and pastures exploit only 1 or 2 m of soil, the water which penetrates to greater depths will recharge the groundwater system under farmland.

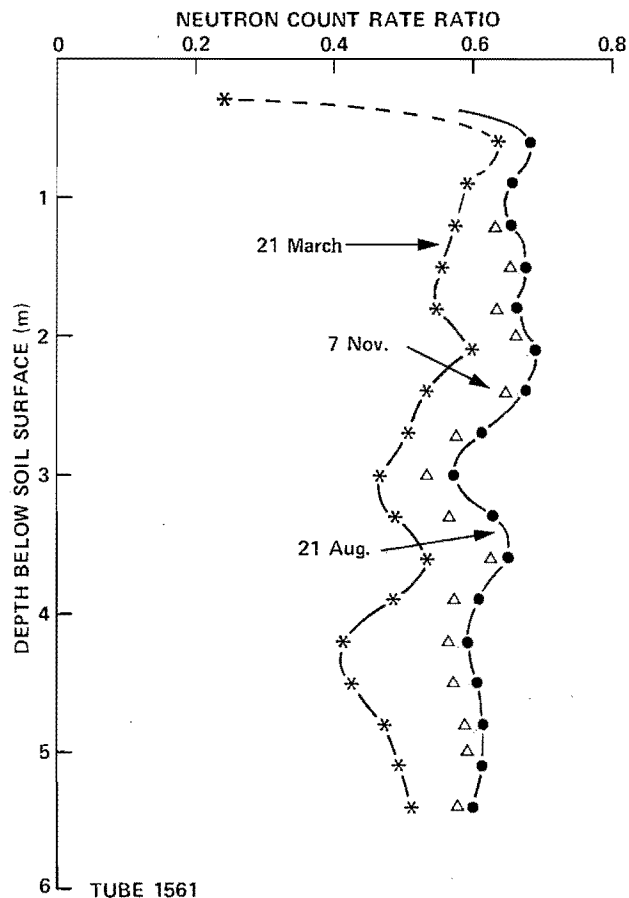


Figure 4. Typical seasonal variation of soil moisture profiles (by neutron logging) in soils under forest in the Darling Range area.

Table 1. Components of the water balance of two small forested catchments (East and West) and tank evaporation at Bakers Hill, WA for 28 day periods in 1971.

		Period Ending													
		1/19	2/15	3/15	4/13	5/10	6/7	7/5	8/2	8/30	9/28	10/26	11/23	12/21	
(1)	Rainfall (mm)	E	12	35	14	63	0	71	38	56	72	118	78	8	18
	W	12	35	13	66	0	73	40	64	67	120	82	2	22	
(2)	Runoff (mm)	E	0	0	0	0	0	0	0	0	2	0	0	0	
	W	0	0	0	0	0	0	0	0	0	0	0	0	0	
(3)	Soil moisture increment <sup>a</sup> (mm)	E	-7	0	-13	19	-14	38	-12	10	5	35	7	-36	-11
	W	-16	-8	-3	15	-8	21	9	12	30	62	1	-40	-62	
(4)	Actual evaporation <sup>b</sup> (mm)	E	19	35	27	44	14	33	50	46	67	81	71	44	29
	W	28	43	16	51	8	52	31	52	37	58	81	42	84	
	Tank evaporation <sup>c</sup> (mm)		250	240	180	110	65	55	55	65	80	120	190	230	250

<sup>a</sup>Averages by neutron method to about 4 m depth. Data from 4 access tubes in E, and 7 tubes in W catchment.

<sup>b</sup>Determined as (4) = (1) - (2) - (3) so that any underflow is included in evaporation. Maximum underflow in a 28-day period is estimated to be less than 1 mm.

<sup>c</sup>Extrapolated monthly data from sunken pans adjusted to the 28-day periods (Australian Water Resources Council, 1968).

A moisture characteristic of the kaolinitic subsoil is shown as Figure 5. It is notable that there is relatively high moisture content at the 15 bar capillary potential. Thus relatively little water will be needed to saturate the soil after it has been dried out by deep rooted plants. This is confirmed from soil moisture measurements which show that under forest moisture storage is about  $4.3 \text{ m}^3 \text{ m}^{-2}$  and an additional  $1.0 \text{ m}^3 \text{ m}^{-2}$  would saturate the profile.

The small excesses of soil water after replacing forest by crop or pasture cause a relatively rapid change of water table elevation. This is associated with accelerated movement of solutes, and the discharge of saline groundwater at the soil surface, or directly into streams. Streams which were ephemeral and losing water to the permanent water table while the catchment was forested flow for a longer period and ultimately gain saline water due to the rise of water table after clearing for agriculture.

From pump tests, the hydraulic conductivity of the permanently saturated zone under forest is estimated to range from  $10^{-5}$  to  $10^{-1} \text{ m day}^{-1}$ , with a median value of order  $10^{-2} \text{ m day}^{-1}$ .

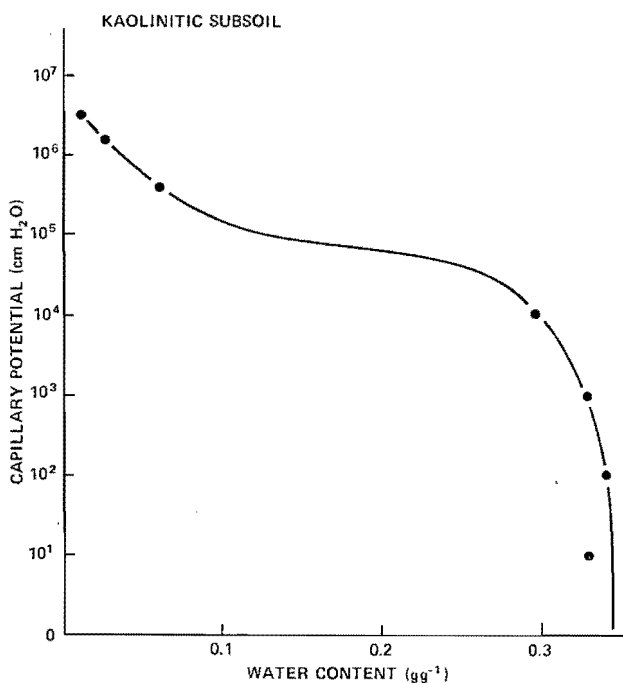


Figure 5. A moisture characteristic of kaolinitic subsoil from the Darling Range area.

**PREDICTING THE EFFECT OF LAND USE ON STREAM SALINITY**

For land management purposes it is essential to be able to predict the effect of the removal of forest vegetation on stream water quality. Peck (1975) has adapted a method originally developed to estimate the contribution of groundwater discharge to total streamflow of a gaining stream (Pinder and Jones, 1969).

Peck (1975) assumes that the effect of the change of vegetation on local recharge of groundwater is known. In the development of the model it is assumed that there is essentially no lag in time or loss in volume between recharge and discharge sites. Furthermore, any increase in direct runoff of surface water is assumed small relative to the increased discharge of groundwater. Then in a small catchment the increase of the flow-weighted average stream salinity  $\Delta c_s$  ( $\text{mg l}^{-1}$ ) is given by

$$\Delta c_s = \gamma(c_g' - c_s)/(1 + \gamma) \dots \dots \dots (1)$$

where

$$\gamma = (a/\beta) (A_c/A_w)$$

and other symbols have the following meanings:

- $c_g'$  = the salinity of discharging groundwater ( $\text{mg l}^{-1}$ );
- $c_s$  = the original flow-weighted average stream salinity ( $\text{mg l}^{-1}$ );
- $A_c$  = the area of changed vegetation (ha);
- $A_w$  = the catchment area (ha);
- $a$  = the increase of yearly recharge caused by the change of vegetation expressed as a fraction of local yearly rainfall;
- $\beta$  = the yearly streamflow before the disturbance expressed as a fraction of the yearly rainfall.

It can be argued that the assumptions made in developing this model tend to bias the result towards an overestimate of the actual stream salinity change. However, there will usually be some uncertainty in the value of  $c_g'$  so that predictions from the model should be considered as first approximations.

This model has been developed for the common situation where there is relatively little data on hydraulic

characteristics of soils in the area. It is likely that simplified models such as this will be used to classify situations where the stream salinity change will be very small, or very large, or of such a magnitude that data should be collected for the operation of a more accurate model.

**THE USE OF VEGETATION TO MANIPULATE THE WATER BALANCE**

While the increases of groundwater recharge resulting from the replacement of native forest by agricultural plants have been sufficient to cause significant changes in stream salinity, the amounts of water involved are small in comparison with the difference between actual and potential evaporation in the area of the Darling Range. Thus there exists a possibility for the use of a relatively small area of phreatophytic vegetation to transpire the water which remains unused when crops and pastures replace forest over part of a catchment. The phreatophytes would be used to dewater or drain the landscape.

From simple water balance equations it is easy to show that the ratio of the areas of phreatophytes  $A_p$  (ha) and pasture  $A_g$  (ha) for total transpiration of the unused water is given by

$$A_p/A_g = \Delta G / (E_p - E_f) \dots\dots\dots (2)$$

Other symbols in this equation represent:

$\Delta G$  = the difference between groundwater recharge under the crop or pasture and the forest vegetation (mm yr<sup>-1</sup>);

$E_p$  = the evaporation rate from the phreatophytic vegetation (mm yr<sup>-1</sup>);

$E_f$  = the evaporation rate from the forest vegetation (mm yr<sup>-1</sup>).

An estimate of average  $E_f$  on a catchment scale may be made from yearly averages of rainfall and streamflow. Similarly, for rough calculations  $E_p$  can be taken as some fraction of tank evaporation  $E^*$ , perhaps 0.75 or 1. The latter value allows for a relatively high transpiration rate from small areas of well watered vegetation which receive advected sensible heat and reflected short wave radiation from surrounding areas of non-transpiring vegetation during summer months.

Using estimated tank evaporation data (Australia Water Resources Council, 1968), and other data from Peck and Hurlé (1973), the ratio  $A_p/A_g$  for the Darling Range area is found to lie generally in the range 0.02 to 0.11 ( $E_p = E^*$ ) or 0.03 to 0.26 ( $E_p = 0.75 E^*$ ). In the case of one catchment where a very large difference between water use of pasture and forest has been estimated,  $A_p/A_g$  is 1 or 3.6.

Thus in most areas the ratio of phreatophytic vegetation to crop or pasture is estimated to be relatively small, of order 10 percent, but in exceptional areas a greater area of phreatophytes than of pasture may be necessary to maintain the original water balance of the area.

The above calculations take no account of the hydraulics of flow of water through the soil from areas of crop or pasture to areas of phreatophytic vegetation. The objective of a planting strategy would be to maintain the unconfined water table at such a depth below the soil surface that salinity problems are minimized or eliminated. An analogy with tile drainage to overcome salinity problems is apparent.

In order to make preliminary calculations, we assume uniform soil overlying a horizontal, impermeable basement. Let the phreatophytic vegetation be planted in parallel rows, and assume that the movement of water to the roots is similar to the groundwater flow to a drainage ditch. Then the classic elliptic equation for the water table can be applied (Van Schilfgaarde, 1957):

$$S = 2 [(H_o^2 - h_o^2) K/G]^{1/2} \dots\dots\dots (3)$$

In this equation symbols have the following definitions:

$S$  = the distance between drainage ditches (or belts of phreatophytic vegetation) (m);

$H_o$  = height of the water table above the impermeable basement midway between the ditches (m);

$h_o$  = height of the water table above the basement in the ditches (or below the phreatophytes) (m);

$K$  = the hydraulic conductivity of the soil (m day<sup>-1</sup>);

$G$  = the average rate of recharge of water beneath the pasture or crop (m day<sup>-1</sup>).

Assuming an average depth of soil on the impermeable basement of 20 m, and a water table of depths of 5 m and 15 m midway beneath the rows, and beneath the rows respectively, then  $(H_o^2 - h_o^2) = 200 \text{ m}^2$ . The median value of  $K$  in the Darling Range is of order  $10^{-2} \text{ m day}^{-1}$ . Values of  $G$  are listed by Peck and Hurlé (1973). Substituting in Equation 3 leads to values of  $S$ , the spacing between belts of phreatophytic vegetation, ranging from 80 to 350 m. The larger spacing is more representative of common values of the groundwater recharge beneath crop or pasture in this area.

These preliminary calculations suggest that suitable varieties of vegetation and planting strategies (area and

distribution) should be effective in modifying catchment water balances and reducing saline seepages into streams and rivers of the Darling Range. Further work is proceeding. One direction is to define areas, if any, within a farmed catchment where reforestation would be most effective. For example, recharge to groundwater is likely to be dependent on soil type, so that it may be possible to use soil maps to decide which areas of farmland should be reforested, or which areas of forest vegetation should be reserved to conserve stream water quality.

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# Changes in the Water Balance with Land Modification in Southern Australia

F. X. Dunin\*

## INTRODUCTION

Since European settlement in Australia, the most apparent forms of land degeneration have been erosion, salting, and a decline in soil fertility. These all reflect changes in the water balance which accompany changes in land use. The concept of ecological stability to achieve permanence in production, either as plant or water yield (Downes, 1959), implies an understanding of the influence of water relations of the soil-plant-atmosphere continuum in maintaining soil chemical and physical features. Thus attention has been directed to the hydrologic consequences of manipulating the soil-plant environment above and below the soil surface to understand the history of Australian land management. In this way, forms of land use which either reverse or prevent declining productivity may be prescribed.

In this paper, studies of hydrologic disturbance are reviewed and interpretations are made for the influence of land modification on the mechanics of water flow. Emphasis is given to the better-documented cases of hydrologic disturbance such as occurs in agricultural areas, mountainous and forested regions. One of the major modifications to land in southern Australia has been urbanization, but this is outside the scope of this review.

### Australian Experience of Hydrologic Disturbance

Hydrologic disturbance induced by land modification has had significant economic consequences in Australia. Accelerated erosion following European settlement (Morland, 1960) has been assessed as affecting 30 percent of the landscape of non-arid Australia,  $2 \times 10^6$  sq. kilometers in extent (Anon, 1971a); the arid region is defined as receiving rainfall that is either inadequate or so unreliable as to prevent the economic management of sown crops. The loss of topsoil caused a decline in agricultural productivity with nutrient loss and alteration of soil

properties to inhibit plant growth. Increased salinity of Australia's largest river, the Murray, resulted from certain irrigation practices within the valley (Anon, 1970a) and poses major problems in water supply along the downstream reaches of the river. Salinization of non-irrigated land has impaired agricultural production, being most extensive in Western Australia with an estimated  $4 \times 10^5$  sq. kilometers lost to cultivation (Anon, 1970b). The removal of trees has been suggested as the major factor for disturbance in this case (Bettenay, Blackmore, and Hingston, 1964).

Removal of trees marked the initial stages of agricultural exploitation and in combination with grazing, probably had the most undesirable effects hydrologically. The impact of clearing, however, varied both in the extent and the form of deterioration experienced. In many instances in humid environments, with annual precipitation exceeding evaporation, degeneration has been limited to losses in soil fertility only, which may be reversed. By contrast, the landscapes of semi-arid to sub-humid environments which exhibit seasonal patterns of soil moisture stress, have undergone significant and sometimes irreversible degeneration resulting in both erosion and salting (Downes, 1958). In arid regions, early grazing management led to changes in the patterns of overland flow of water resulting in alterations to the character of plant communities.

In areas of low soil fertility and unreliable rainfall, the landscape became modified by sequential development of bared areas, soil detachment and crusting, which in turn reduced infiltration and increased overland flow. Furthermore, absence of vegetation lowered evaporation rates resulting in changes in soil water flow. Fluxes of soil water were often generated in saline soils leading either to salt transport in solution (Cope, 1958) or to subsoil dispersion and erosion (Downes, 1946). This changed the character of streamflow such that ephemeral flows became more pronounced and carried an increased amount of materials in suspension and solution. It was only during the rural reconstruction program of the 1940's that initiatives based on improved conservation technology arrested land deterioration and that programs of soil and water conservation were undertaken seriously.

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The aim of soil conservation has been to minimize overland flow by either restoring or maintaining the infiltration capability of soil using both vegetative and mechanical techniques. The most concerted effort in southern Australia was undertaken in agricultural regions of the semi-arid to sub-humid environment and this had led to some success (Anon, 1971a). A growing desire to apply principles of conservation to a wide range of catchment resources has accompanied this recovery and requires an understanding of soil-plant-water relationships for a wide range of environments. Documented studies of hydrologic response to disturbance, described in the following sections, provide a basis for such understanding and are reviewed in the following section for three ecological regions of southern Australia.

### EXAMPLES OF HYDROLOGIC DISTURBANCE

#### Grazing Areas in Semi-arid and Sub-humid Regions

Downes (1958) concluded, for catchments with rainfall less than the potential evaporation, that degeneration was associated with a reduced water use and greater amounts of rainfall excess either as surface runoff or soil water flow. At Bacchus Marsh, Victoria, an eroded catchment of native grasses produced more runoff than a catchment in its natural condition (Dunin and Downes, 1962). Model studies, summarized in Table 1, show that sorptivity inferred from hydrographic analysis (Dunin and Costin, 1970) was greater for the better vegetated catchment (6). This comparison suggests that the contrast in runoff yield may be attributed to differences in infiltration characteristics which in turn favor greater evaporation from the catchment with natural vegetation (Dunin, 1970).

Evaporative rates were similar, however, for both catchments with ample supplies of soil water, though they were sustained for shorter periods from the degraded catchment (3). The non-degraded catchment (6) was

**Table 1. Comparison of runoff, infiltration, and evaporative characteristics for eroded catchment (3) with catchment of natural grassland (6).**

	Eroded Catchment (3)	Natural Grassland Catchment (6)
Average Annual Rainfall (4 year av.) (mm)	524	524
Av. Annual Yield of Runoff (4 year av.) (mm)	46	26
Infiltration Characteristics		
Sorptivity at (cm min <sup>-1/2</sup> ) $\theta_0 = 0.20$	0.14	0.21
Evaporative Characteristic $E_p/E_0$	0.99	0.98

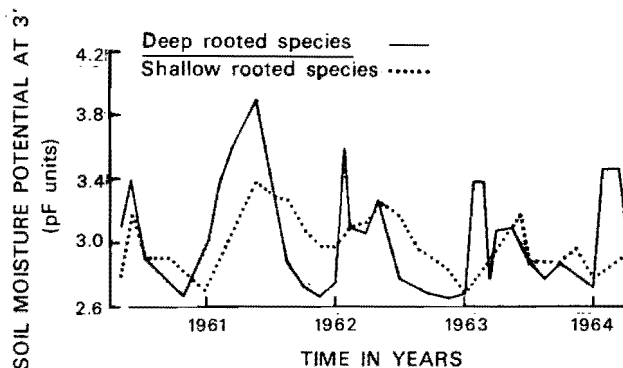
$E_p$  = evaporative rate with abundant supply of water.  
 $E_0$  = evaporation from an Australian dunken tank evaporimeter.  
 $\theta_0$  = initial volumetric soil moisture fraction of limiting layer.

composed of natural grassland, the major species of which have a deep-rooting habit and exploit subsoil moisture more effectively than degraded pasture. This contrast is shown in Figure 1 in which the fluctuations in subsoil moisture potential are greater under natural grassland than under the degraded condition.

Conversion of grassland to sown species for greater grazing or silvicultural production has reduced water flow either by reducing runoff or recharge to groundwater or both, e.g. natural grassland to improved pasture (Dunin and Downes, 1962) and improved pasture to a forest of *Pinus radiata* (Colville and Holmes, 1972; Allison and Hughes, 1972). In these examples, reduced flow has been attributed to increased evaporation by the introduced community but without detectable change in infiltration characteristics (Dunin, 1970; Holmes and Colville, 1970a, b). This finding supports Boughton's (1970) view that much of the reduction in runoff accompanying changes in vegetation may be traced to an enhanced infiltration indirectly induced by evaporative characteristics rather than being the direct result of changes in soil properties.

Table 2 shows reduced annual yields of runoff with pasture improvement of both an eroded and a natural grassland. In comparing the influence of treatment on catchment characteristics, sorptivity, although different for the initial conditions, remains unchanged with treatment. The evaporative characteristic, which is similar for both initial conditions, in both cases increases with the introduction of the improved pasture. These data suggest that the evaporation process is sensitive to a change in botanical composition whereas infiltration is increased due to greater soil moisture deficits caused by enhanced evaporation from the introduced species.

An unexpected outcome of pasture improvement has been that yield reduction in the annual hydrograph is not necessarily associated with a diminution in peak discharge (Dunin, 1965). Table 2 shows that the peak flow observed over a 4 year period is not reduced as the result of pasture improvement in either conversion. In fact, for the



**Figure 1. Fluctuations in moisture potential of subsoil for contrasting conditions of natural grassland at Bacchus Marsh, Victoria. (After Dunin, 1970).**

conversion of natural grassland, the peak flow has increased despite yield reduction suggesting an induced erosion hazard. In this case, pasture improvement involves replacement of perennial native grasses by annual species with reduced vegetative cover in summer. This is the time when intense rainstorms and major peak flows are most likely in small rural catchments of southern Australia. For the remainder of the year major contributions to water yield occur during the growth of introduced species. In this period, evaporation by the introduced pasture is greater than for natural grassland irrespective of erosion history. In this way infiltration is increased on an annual basis. The net effect of pasture improvement is a reduction in annual yield of runoff but without ensuring complete erosion control. Such a situation calls for complementary measures to combat summer erosion. At Wagga, New South Wales, mechanical means of erosion control, such as contour banks, have been used effectively for complete erosion control with significant reductions in both the annual yield of runoff and peak discharge (Soil Conservation Service of N.S.W., pers comm.).

At Mt. Gambier, South Australia, the annual evaporation from pine forest, determined by water balance techniques, is greater than that from grassland (Figure 2) to reduce recharge from a sandy soil to groundwater. For the winter-spring period, the pine evaporation may be twice that of grassland (Holmes and Colville, 1970b). To better understand this difference, micrometeorological techniques for determining the atmospheric water vapor flux have been used to follow the dynamics of evaporation in more detail. The observations indicate greater evaporative rates from pines than from grass while the canopies are wet (Moore, 1975). For day surfaces during periods of abundant soil water (generally autumn, winter, and spring at Mt. Gambier), transpiration dominates the evaporation process and the vapor flux appears to be greater from grassland. These findings are consistent with the theoretical study of Monteith (1965) in the United Kingdom. Thus, increased annual evaporation of pine forest over grassland at Mt. Gambier may be attributed to greater interception of the rainfall (falling mainly during

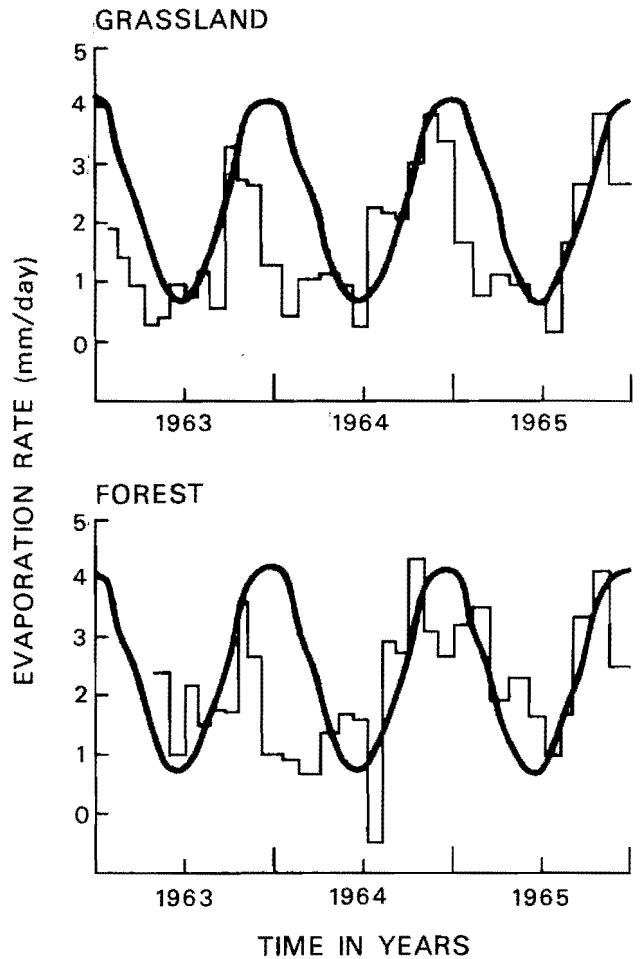


Figure 2. Comparison of grass and pine evaporation at Mt. Gambier, S.A. Histograms represent the time averaged rate over periods used in the water balance techniques for determining evaporation. The superimposed curve is the potential evaporation rate. (After Holmes and Colville, 1970a, b).

Table 2. Runoff, peak flow, infiltration, and evaporative characteristics determined over 4 year period for natural and improved pasture.

Catchment No.	2	3	5	6
Catchment Area				
Initial Condition	Eroded Natural Grassland		Natural Grassland	
Post Treatment Condition	Annual improved pasture	Eroded natural grassland	Annual improved pasture	Natural grassland
Av. Yield of Runoff (mm)	23	46	3	26
Peak Flow (cumec X 10 <sup>-3</sup> )	81	80	47	11
Infiltration Characteristic				
Sorptivity at $\theta_0 = 0.20$ (cm min <sup>-1/2</sup> )	0.12	0.14	0.24	0.21
Evaporation Characteristic				
$E_p/E_0$	1.08	0.99	1.07	0.98

the nine cooler months) in combination with an enhanced vaporization rate from this store. During periods of soil moisture stress, transpiration may increase the difference in vapor loss between pine forest and grassland because of the deeper rooting habit of pines.

With an understanding of the relative importance of water flow processes in Australian agricultural systems and their sensitivity to changes in surface conditions, some hydrologic responses to landscape modification may be interpreted in physical terms:

- Runoff reduction, accompanying pasture improvement. Reduction may be attributed to greater evaporation by introduced species and thereby promote infiltration. This is of benefit for greater erosion control but may reduce supplies of farm water (de Laine and Vasey, 1961).
- An increased soil water flux in saline soil. This may induce accelerated leaching of solutes which salinize adjacent land (Peck, 1975) or, in sodic soils, the dispersion and erosion of subsoil. Removal of deeper-rooted vegetation reduces plant evaporation in these environments and so maintains higher moisture in the subsoil which favors downward movement of soil water during subsequent rains. Salinization has, however, also been noted in the presence of some introduced pasture species (Holmes, Leeper, and Nicholls, 1939, p. 177). In this case, soil water extraction, although increased for certain periods, was limited to a shallower depth and the net result has been to generate a greater low of subsoil water than occurred under the indigenous community.
- Fluctuations in groundwater following manipulation of vegetation change. As for salinity, the presence or introduction of deep rooted species depresses recharge of groundwater whilst removal of these species has induced a rising water table, sometimes with undesirable consequences (Mezler, 1962).
- The development of erosion hazards in nonarable grazing country in southeastern Australia following aerial topdressing with fertilizer (Rowe, 1967, p. 108). This practice promotes growth of annual introduced species at the expense of perennials and leads to reduced protection of the soil surface during summer thunderstorms. Mechanical forms of protection are not possible in such topography and attempts to re-introduce perennial species have not been very successful (Anon, 1971b, p. 31).

In summarizing these physical interpretations of hydrologic disturbance, some generalizations may be drawn from the impact of grazing management and soil conservation practice on river discharge. Sub-catchments,

managed for agriculture by either cultivation or grazing, are major contributors of suspended material in river discharge (Hexter, Leslie, and Pels, 1956) and soil conservation practices for reduction of sediment load are concentrated in these regions. Furthermore, Australian experience with "dry land" salinity indicates that proper management of these catchments may be critical to reduce transport of solutes. Thus, the price for water quality control may be a reduction in the quantity of streamflow but the extent of reduction is unknown.

Available evidence suggests that no major change in the yield of river discharge in southern Australia has occurred due to landscape modification during the period of gaging (Boughton, 1970). This may be due to the small contributions to streamflow from agricultural areas (despite extensive catchments) in comparison with that produced by upland humid sub-catchments. Another possibility is that modification is neither sufficiently extensive nor systematic to noticeably affect yield. As patterns of agricultural land use change continually and with them the local water balance, their influence on yield modification in river basins cannot be dismissed. Physical process models appeal for forecasting variation in yield as a result of land manipulation (Larson, 1972).

#### **Mountain Regions Experiencing Regular Winter Snowfall**

The high country of southeastern Australia forms the catchment areas for important conservation programs which supply water for hydro-electricity and irrigation. These areas have a long history of summer grazing and burning and consequent damage to vegetation and soils (Anon, 1957). Since quality and rate of runoff of water are critical to water conservation, grazing pressure by domestic livestock ceased above 1400 m in 1958.

The combination of grazing and fire regimes changed the nature and amount of vegetation cover, especially in grasslands (Costin et al., 1959). Surface runoff and soil loss increased as vegetative cover decreased. With the replacement of snowgrass by shrubs, further deterioration occurred as woody and sclerophyll vegetation is less effective for promoting infiltration than herbaceous material. Residence time of snow is least on bare areas thereby compounding impaired infiltration with freezing of the unprotected surface. Thus, ground cover standards have been specified to combat erosion, viz., 12 tonnes/hectare of herbaceous material or 27 tonnes/hectare of sclerophyll material being recommended for control (Costin, Wimbush, and Kerr, 1960). Owing to the shrinking and dissection of sphagnum bogs, located at outflow points of sub-catchments in grasslands, there has been a further loss of streamflow regulation by biological influences.

These observations have come from ecological surveys and have been more quantitatively substantiated from plot

studies of runoff behavior; they serve as a reference in determining future management of mountain catchments, particularly in relation to control burning.

Modifications to mountain forests also have induced hydrologic disturbance with influences on both precipitation and infiltration. Strip cutting of the community provides opportunities for increasing snow accumulation and retarding the rate of its melt (Costin, 1967). Wild-fire in mountain forests produces large increases in runoff and sediment, presumably with the mechanics of water flow responding similarly to those in grasslands. Such catchments have assumed their pre-fire characteristics after 5 years without the grazing pressure of domestic stock (Brown, 1972).

The mechanics of reduced infiltration and accelerated erosion resulting from decreases in ground cover have not been clarified. The hypothesis is that with decreases in ground cover, infiltration capacity is reduced and there is a loss of structure of the soil surface and the incidence of soil freezing is increased. Accompanying this change in surface condition is a diminished evaporation rate which aggravates the problem of impaired infiltration. It is important to note that, in this environment, the slow regeneration of vegetation after disturbance retards the recovery in infiltration properties (Costin, Wimbush, and Kerr, 1960).

#### Rainfed Forested Areas

Forests generally occur in high rainfall regions of Australia's river systems. Consequently, their contribution to streamflow is particularly important in a country that is extensively semi-arid to arid, and their management is critical in maintaining a water supply of acceptable quality for urban and rural needs.

Australian forests are usually dominated by eucalypts. Little is known of their properties concerning water transport. Accordingly, case studies of the hydrology of eucalypt communities demand attention, especially in relation to replanting with coniferous forest and to their management for water supply.

Conversion of eucalypt forests to coniferous forest is widely practiced in southern Australia but with little information available on streamflow yield. Smith, Watson, and Pilgrim (1973) provided some preliminary information on the hydrologic consequences of such conversion for catchment experiments at Lidsdale, N.S.W. Runoff was less from the coniferous catchment over 2.5 years. The difference has been attributed to an increased amount of evaporation from interception (Table 3). Such reductions in runoff are not necessarily general, as Costin and Wimbush (unpublished data)—using a water balance technique at Jounama, N.S.W.—suggest that while there may be seasonal differences in evaporative loss from the respective forests, annual evaporation from both communities may be the same. This implies that the greater water loss in pines

from interception can be compensated for by increased transpiration from eucalypts, with temporal distribution of rainfall being a significant factor for the partitioning of vapor losses between interception loss and transpiration.

The practice of reserving intact eucalypt forest solely for purposes of domestic water supply has been debated vigorously. Critics claim that both water and catchment timber resources can be satisfactorily managed in the one area. To support the claim for reservation, Langford (1974) cites a change in streamflow pattern near Melbourne, Victoria, following the disastrous fire of 1939. Before the fire, catchment vegetation was a mature mountain ash (*E. regnans*) forest but with fire and death of mature trees, the character of the stand has changed with large areas of regenerating forest of the same species. Using trend analysis, Langford suggests that no detectable change in streamflow behavior has occurred for the 5 years immediately after the fire. However, in subsequent years, water yield has progressively declined to a minimum at about 25 years after which the trend appears to be reversed. This sequence may be explained in terms of the proportion of regenerating forest in the community transpiring at a greater rate than mature forest, and there is some plant physiological evidence to support this explanation. However, measurements of the respective evaporative rates are needed for a more detailed analysis of fire disturbance in this community. It is noteworthy, however, that this response to fire in streamflow is different from that of forested catchments in the mountain environment (Brown, 1972).

Fire sensitivity of the permeable krasnozems soils of the *E. regnans* community provides an explanation for the difference in infiltration response to fire in this lowland forest compared to that inferred for the mountain areas. When surface temperatures exceed 400°C, soil structural changes occur which, although rendering them more erodible, induces an increased permeability and resistance to surface sealing (Craig, 1968). These temperatures were likely in the 1939 fire thereby favoring absorption of rainfall subsequent to the fire even without the protection of vegetation for maintaining infiltration properties. Thus, in view of the unchanged hydrologic response immediately after the fire, the pre-fire characteristics to minimize overland flow were maintained in the lowland forest whereas

**Table 3. Components of water balance (mm) of contrasting forests at Lidsdale, N.S.W. for 31 month period. (After Smith, Watson, and Pilgrim, 1973).**

	Pine Catchment	Eucalypt
Precipitation	2207	2268
Interception	414	241
Runoff	183	323
Soil moisture increase over period	23	89
Evapotranspiration	1587	1615

5 years were required for their recovery in the mountain areas.

### CONCLUDING REMARKS

Studies of disturbance to the water balance in agricultural, mountainous and forested catchments have been reviewed. These catchments represent some of the areas where significant modifications to the landscape have occurred in southern Australia. Evaporation is sensitive to disturbance, but because of interaction with other processes and catchment characteristics, the impact of its change on the water balance varies with the nature of the disturbance and with environment. Some unexpected, if not unique, responses to disturbance have been described which emphasize the need for caution in extrapolating measured changes in streamflow regime.

Mathematical models with a physical rationale facilitate the analysis and prediction of the hydrologic consequences of land manipulation. This approach must be based on detailed information on the meteorology and the important properties influencing catchment response. Such information is not generally available and the extensive acquisition of appropriate data is a necessary step for land use planning. In particular, the study of evaporation from eucalypt forests, because of its importance to urban water supply and river discharge, deserves high priority for future research.

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# Land Surface Modifications and Their Effects on Range and Forest Watersheds

J. Ross Wight\*

## INTRODUCTION

Forest and rangeland are broad land classifications and include wide ranges of environmental and vegetational regimes. According to Tueller and Colbert (Branson et al., 1972) approximately 70 percent or 9.7 billion ha of the earth's land surface is considered forest or rangeland. About 63 percent (490 million ha) of the conterminous United States is classified as forest or rangeland (U.S. Forest Service, 1972). This vast forest-range complex has a wide array of multiple-use products of which water is the most important. Water is used on-site in the energy fixing processes of photosynthesis and off-site from surface and groundwater sources for domestic, industrial, and agricultural purposes. Because 80 percent of the world's rangelands are arid or semiarid, water is the major growth limiting factor in forage and timber production. Sparsity of vegetation on arid and semiarid watersheds contributes to problems of runoff and incident flooding, sedimentation, and erosion. Thus, most land-surface modification treatments have been developed and applied for retaining precipitation where it falls thus increasing soil water and subsequent forage production and controlling runoff and erosion.

Land-surface modification treatments affect the hydrologic cycle and watershed characteristics in many ways (Figure 1). Usually, runoff and subsequent erosion are reduced by impoundment or retention of rainfall and snowmelt and by an increase in soil permeability which usually accompanies mechanical treatments. As more water enters the soil, watershed vegetation is usually modified in a direction beneficial to runoff and erosion control. Also, as surface runoff is reduced more precipitation enters the soil increasing evapotranspiration and, sometimes, groundwater supplies.

There are also indirect effects of land surface modification on watersheds. Mechanical disturbance of native sod temporarily increases soil fertility as the disturbed soil and organic matter weather and decompose. Species compositions are altered as disturbed areas begin

secondary successions and, when microenvironmental factors like soil water are significantly altered, the climax species will be different than those originally present. Species compositions are also changed when treated areas are seeded to native or introduced species.

Snow trapping is an important facet of surface modification treatments. As vegetation responds to a more mesic soil water regime, more crop residue is usually available to trap and hold snow during winter months.

## LAND SURFACE MODIFICATION TREATMENTS

### Level Bench Terracing

Level bench terracing is one of the most severe and expensive land-surface modification treatments applied to rangeland. Although similar systems have been used for several thousand years in other countries, it is only in the last two or three decades that they have been adapted for use as a soil and water conservation practice in annual cropping systems in the Great Plains States. Haas and

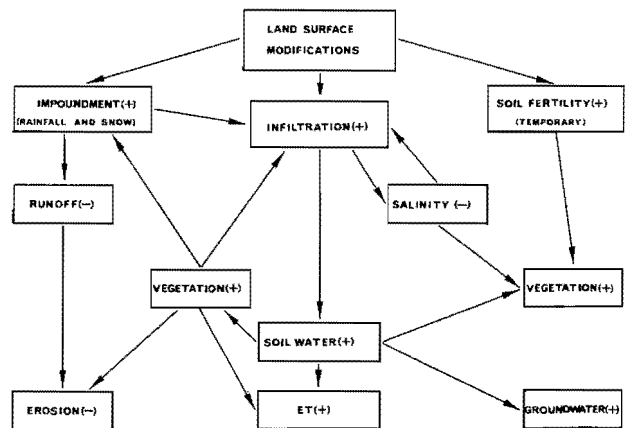


Figure 1. Effects of land surface modifications on Forest-Range watersheds. An increase or decrease in factor magnitude is indicated by (+) and (-), respectively.

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Willis (1968) were among the first to use level bench terraces on rangelands to increase forage production.

Level benches are best described as long, flat terraces, level in all directions, and diked at the ends and front to provide a water storage capacity. As indicated in Figure 2, level bench systems can be built or constructed with or without contributing areas. At Mandan, North Dakota, Haas and Willis (1968) and McMartin et al. (1970) worked with level benches 9 and 15 m wide, accompanied by contributing areas of 0 to 85 times the bench width. Slopes in these studies ranged from 5 to 10 percent. Rauzi et al. (1973) studied two widths of level benches—8-m widths on 1 to 6 percent slopes and 4-m widths on 6 to 12 percent slopes.

Level benches can effectively increase soil water recharge and subsequent forage production. Haas and Willis (1971) reported results of a 5-year study wherein overwinter water storage averaged 3.6 cm on nontreated slopes and ranged from 12.2 to 23.1 cm on level benches. Alfalfa production averaged 3360 kg/ha on untreated slopes and ranged from 7200 to 9590 kg/ha on level benches. In another study (Haas and Willis, 1968), bromegrass production was increased from 1000 kg/ha outside level benches to 1850 kg/ha within level benches. With applications of N, bromegrass yields were 2120 and 3520 kg/ha, respectively. However, not all level bench treatments have been as successful. Rauzi et al. (1973) planted alfalfa, crested wheatgrass, intermediate wheatgrass, and alfalfa wheatgrass mixtures on level benches, and only alfalfa had a significant yield response. There was no measurable forage response the second crop year due to lack of snow catch in the level benches during the preceding winter.

From the above reported studies, it was found that benefits of a contributing area were insignificant; soil water increased mainly from trapped snow; benches should be oriented to take advantage of prevailing winds to

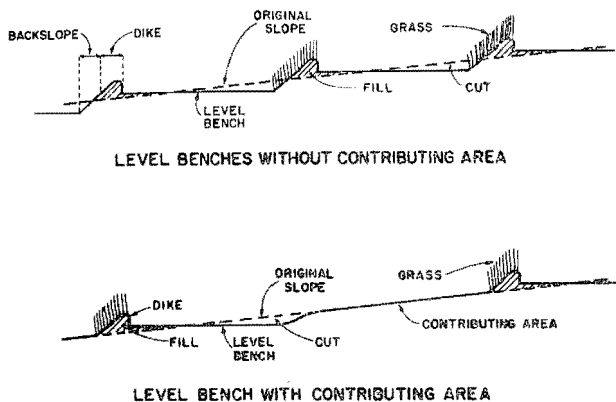


Figure 2. Diagrammatic profile of level benches with and without contributing areas (McMartin et al., 1970).

trap the most snow; and to take maximum advantage of increased soil water, fertilizer, particularly nitrogen or phosphorus for legumes, must be applied. In a related study, Black (1968) found that topsoil removal in forming bench terraces was very detrimental to plant growth and that replacing 2 to 5 cm of topsoil increased yields by as much or more than the highest rate of commercial fertilizers. One of the first rangeland terracing attempts was unsuccessful because fertile topsoil was removed to build the dikes (Cox et al., 1971).

### Contour Furrowing

Contour furrowing was one of the first land-surface modification treatments to be applied to U.S. rangelands. Bennett (1939) who described several contour-furrowing techniques indicated that contour furrows were the end product of an evolutionary process in which pasture terraces were constantly made smaller and brought closer together. According to Caird and McCorkle (1946), over a 400,000 ha of pasture and rangeland were contour furrowed between 1934 and 1940, and Coltharp (1967) estimated that an equal amount has been contour furrowed since then.

Furrows and furrowing equipment have varied in shape and size. Furrows have been spaced as far as 15 m apart to as close as 0.6 m. Optimum spacing is closely related to furrow size with small furrows requiring the narrowest spacing. Generally, furrow spacing greater than 1.5 to 1.8 m has been ineffective (Bennett, 1939; Barnes, 1950). Moldboard plows and various versions of lister plows were first used to contour furrow rangeland. Also furrowers have been specially designed such as the Kansas and Iowa Furrowers (Branson et al., 1966).

The most recent and popular furrowing implement, the Arcadia Model B contour furrower (Figure 3), was developed by the U.S. Forest Service. As described by Valentini (1971), this implement makes two furrows 150 cm apart, ranging from 46 to 76 cm wide and up to 20 cm deep. Furrow openers are two offset disks which throw the soil in opposite directions. The openers are preceded by rippers which are adjustable to a 30-cm depth below the furrow bottom. Intrafurrow dams can be constructed every 3 to 30 m with a four-paddle dammer. This furrower can also be equipped with a broadcast seeder.

Contour furrowing affects soil water recharge in at least three ways: (1) rainfall and snowmelt runoff retention, (2) improved infiltration, and (3) snowtrapping. Retention of water that would normally be lost as runoff is probably the major benefit of contour furrowing, and treatments have been most effective on sites with moderate to high runoff rates (Branson et al., 1966). Water holding capacity varies not only with furrow shape and construction but also with age. Branson et al. (1966) reported that water storage capacity of furrows, newly constructed by the Arcadia Model B furrower exceeded 5.1



cm, but after 7 years, leveled off at about 1.3 cm. Neff (1973) working with similarly constructed furrows on solonchic range sites in eastern Montana, found that water-holding capacity was reduced from a theoretical 6.4 to 2.3 cm during the first 6 months as a result of intrafurrow dam compaction and silting-in of the freshly constructed furrows. The intrafurrow dams were constructed of loose, unconsolidated soil which when wetted compacted to about half its original height. Based on results of this study, Neff (1973) estimated that water-storage capacity of contour furrows on solonchic range sites is reduced to about 0.5 cm in 7 years and to 0.1 cm in 25 years.

Constructing furrows on the contour has been recognized as a major problem (Anderson and Swanson, 1949; Neff, 1973). As furrows deviate from the contour, they tend to concentrate water and increase the runoff and erosion potential. Effective intrafurrow dams offset this hazard. However, where dams are constructed of unconsolidated soil material scraped off furrow bottoms, they compact and are easily breached and eroded. Neff (1973) suggested that a furrowing machine designed to lift the furrowing disks or shovels out of the ground at 4.6- to 6.1-m intervals leaving 0.6 or 0.9 m of undisturbed sod as intrafurrow dams would circumvent this problem. A machine of this type has been constructed and is being evaluated (Wight, 1973).

By retaining precipitation in place, contour furrowing effectively reduces runoff. In central Nebraska, contour-furrowing treatments reduced runoff 84 to 95 percent on a native range site (Wasser et al., 1957). On a solonchic range site in eastern Montana, annual runoff averaged 9.1 cm on untreated watersheds and 2.5 cm on contour-furrowed watersheds (Earl Neff, unpublished data). In the southern Great Plains, small lister furrows spaced 2.1 m apart reduced runoff by about 150 percent (Whitfield and Fly, 1939). Simonson (Workman and Keith, 1973) working in southeastern Utah with contour furrows spaced 7.6 m apart credited the furrowing and gully-plug treatments with reducing erosion by only 11 percent.

Contour furrowing usually improves infiltration. In southeastern Montana, contour furrowing increased infiltration rates from less than 0.5 to 2 cm/hour or more for up to 7 years after treatment (Soieth et al., 1974). Decreases in infiltration rates after treatment were related to an increase in bulk density and a silting-in of fine soil separates from furrow ridges.

Snow trapping varies with type of furrow, vegetation associated with the furrow, and climate. In eastern Montana, contour-furrowed areas trapped about 6.4 cm/year of snow water over a 5-year period as compared with 4.1 cm/year on the nonfurrowed areas. However, nearly all of the snowmelt was lost as runoff from the

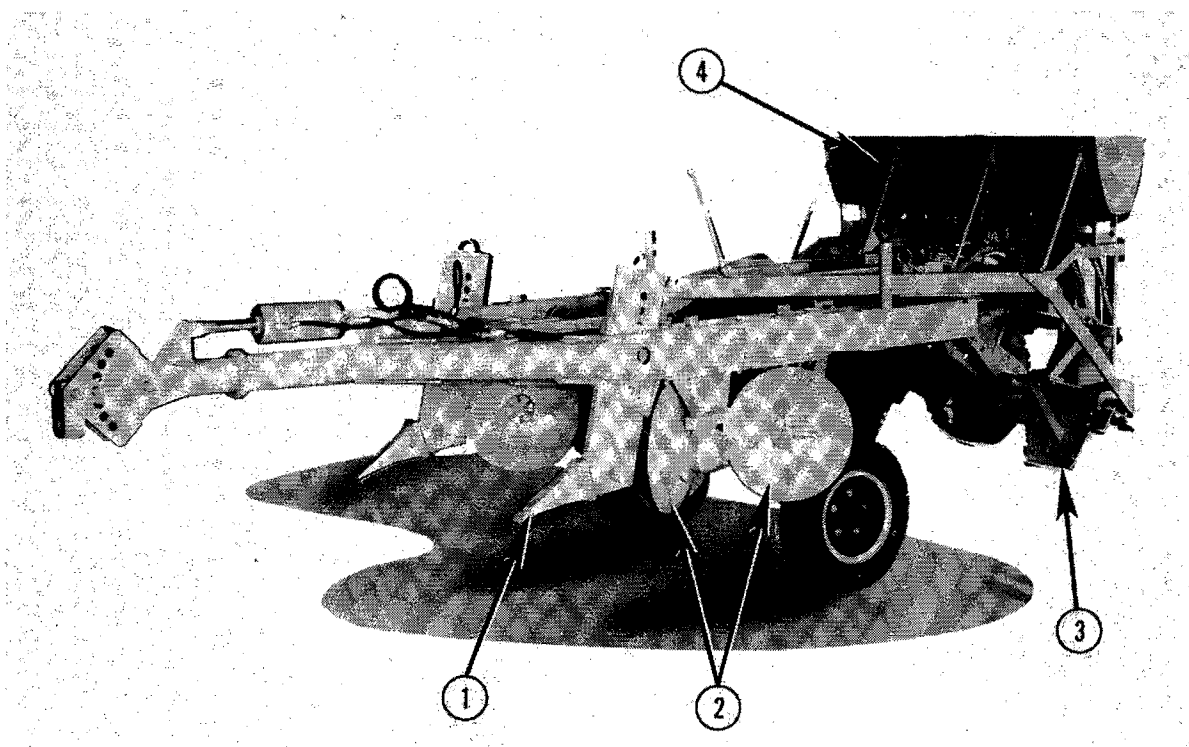


Figure 3. Contour Furrower. Major components are: (1) subsoilers, (2) disc furrowers, (3) dammers or blockers, and (4) seeder (U.S. Forest Service, 1970).

nonfurrowed areas, whereas, only about half was lost from the furrowed areas (Wight et al., 1975).

Contour furrowing beneficially affects forage production in at least four ways: (1) improved soil water regime, (2) improved soil physical and chemical properties, (3) improved species composition, and (4) improved soil fertility. In Nebraska, Dragoun and Kuhlman (1968) reported that contour furrowing rangeland in low condition class increased soil water by about 1.2 inches. In the southern Great Plains, Langley and Fisher (1939) reported that contour furrowing increased the depth to which the soil water penetrated. On solonchic soils which are characteristically impermeable, contour-furrowing treatments more than doubled the amount of water available to plants. In southeastern Utah, on furrows spaced 7.6 m apart, Coltharp (1967) reported soil water increased only in the immediate vicinity of the furrows. On the same furrowing treatments, Wein and West (1971) studied the effects of contour furrowing on the microenvironment as it was associated with seedling establishment and survival. They found that furrowing increased soil water in furrow bottoms but had little effect elsewhere.

Physical and chemical properties of the soil are altered under contour-furrowing treatments. Bulk densities are reduced by mechanical disturbance but with time tend to recompact to their original pretreatment levels (Soiseth et al., 1974). As bulk densities are decreased and infiltration increased, more water is leached through the profile causing a downward movement of salts (Branson et al., 1969; Wein and West, 1973; Soiseth et al., 1974). The process tends to be autocyclic; as more water moves through the soil profile, more salts are leached downward and sodium absorption ratios are often reduced leading to improved soil structure and infiltration. As more water moves into the soil, plant growth is increased, resulting in an increase in soil organic matter and residue on top of the soil which in turn favors improved infiltration.

Changes in species composition result from invasion or reinvasion of the disturbed areas by indigenous species or by direct seeding of exotic species. Often, disturbed areas are initially invaded by weedy species and later by a higher successional order of perennial grasses and forbs. Rhizomatous species, like western wheatgrass, rapidly invade disturbed areas and often constitute a major portion of the forage response to contour-furrowing treatments. Reinvasion by native species or establishment of introduced species in furrow bottoms immediately after treatment is sometimes restricted because topsoil has been removed exposing layers of subsoil which are infertile, high in clay, and/or salt content. On solonchic range sites in southeastern Montana, initial reinvasion and seedling establishment took place on furrow edges. However, after about 10 years, most of the furrowed area was completely revegetated.

Soil fertility effects associated with mechanical treatments are temporary resulting from release of plant

nutrients as disturbed soil and organic matter weather and decompose. Their effects are often overlooked and have confounded treatment effects on short term experiments. Ryerson et al. (1970) reported this short term fertility effect in conjunction with pitting and scalping treatments. Plant samples from contour-furrowed plots had higher nitrogen and phosphorus content than samples from untreated plots.

Forage responses to contour furrowing have usually been positive and yield increases of 100 percent or more are common (Branson et al., 1962; Nichols, 1964; Wight and Neff, unpublished data). However, on widely spaced furrows in southeastern Utah, contour furrowing reduced forage production (Workman and Keith, 1974). In summarizing results of their economic analysis of contour furrowing and gully plug treatments, they concluded that these treatments were physically and biologically ineffective and economically unsound. The longevity of contour-furrowing treatments is a crucial economic factor. While longevity is a function of several factors such as soil, slope, furrow size and design, and quality of treatment application, reported longevities have ranged from as few as 7 to an estimated 25 years (Caird and McCorkle, 1946; Brown and Everson, 1952; Neff, 1973). In northcentral Wyoming, a furrowed area seeded to crested wheatgrass produced 54 percent more forage 15 years after treatment than the nontreated area (Fisser et al., 1974). Broad-base lister furrows (60 to 90 cm wide and 8 to 16 cm deep with undisturbed intrafurrow dams) (Wight, 1973) are much less susceptible to silting-in and erosion than the conventional V-type furrows, and therefore, should be more permanent.

Contour furrowing is an effective means of seeding exotic species into rangeland. In eastern Montana, yield increased up to 300 percent on contour-furrowed plots seeded with crested wheatgrass (*Agropyron cristatum*), Russian wildrye (*Elymus junceus*), regar bromegrass (*Bromus biebersteinii*), and alfalfa (*Medicago sativa*). Species of dryland alfalfa have been successfully established in contour furrows on both solonchic and medium-textured upland range sites. Responses to fertilization in conjunction with contour furrowing have been excellent especially when furrowed areas were seeded to high producing exotic species. On a panspot range site in southeastern Montana, yields were increased from 200 or 300 kg/ha to several thousand kg/ha with combinations of introduced species and nitrogen fertilization (Wight, 1973). Because nitrogen is inherently deficient on native range sites, the seeding of legumes like alfalfa in conjunction with contour furrowing holds real promise as a method of maintaining adequate nitrogen levels.

Similar to contour furrowing is the scalping treatment described by Ryerson et al. (1970) or the lister interseeding described by Wight and White (1974). This treatment is a somewhat mild version of contour furrowing and is applied specifically for the purpose of creating a seedbed in which native species can be reintroduced or

introduced species can be established. The furrows are constructed without intrafurrow dams and may or may not be on the contour. Although any water conservation effect is usually secondary, Ryerson et al. (1970) reported significant soil water gains as a result of this treatment.

Today, contour furrowing is not used as extensively as it was in the past primarily due to a reduction in use on public domain. For individual ranchers, it is expensive and requires specialized equipment. A lister-furrowing implement, such as described by Wight (1973) that could be pulled by a farm tractor and is relatively inexpensive, would make contour furrowing more available to the average rancher.

A major objection by ranchers and range managers to contour furrowing and other land surface treatment is the rough surface left by these treatments. Vehicle travel is greatly restricted and livestock movement is affected. Cattle, at least initially, are somewhat reluctant to graze treated areas. Sheepmen are apprehensive about contour furrows and similar treatments because sheep may get stuck on their backs in the furrows. Some game managers claim that these treatments interfere with the wildlife movement and habitats, particularly for antelope. Except for the effects of the rough terrain on vehicle travel, little evidence is available to support these objections to furrowing treatments.

### Pitting

Range pitting is a land-surface modification treatment that came into practice during the 1930's. This treatment was designed to conserve water by preventing runoff. In some areas of the southwest, pitting has been used to improve the soil water environment for establishment of grass seedlings. The earliest reported research, dealing with this land-surface modification treatment, was from eastern Wyoming (Barnes and Nelson, 1945). Since then, many experimental results from the Great Plains and the southwest as well as good literature reviews have been published (Taylor, 1967; Vallentine, 1971).

Equipment simplicity and application ease have made range pitting a popular practice. The conventional pitting implement is a one-way disk modified either by re-drilling and mounting on eccentric centers or by cutting away a part of the disk and leaving the original mounting position on the shaft (Figure 4). Typical pits formed by either of these modifications are described by Ryerson et al. (1970) as approximately 76 cm long, 20 cm wide, and 10 cm deep. Pits and overturned sod covered approximately 45 percent of the ground surface.

Other implements used to apply pitting treatments include the rotary-drum pitter and rotary subsoiler (Vallentine, 1971). These implements consist of a series of spiked teeth mounted in rows which punch small holes on approximately 91-cm grids up to 36 cm deep. This

treatment is designed primarily to rupture the subsoil and provide indentations for water retention. Storage capacity of these indentations are approximately 8 mm (Wight and Siddoway, 1972). The effects of these pitting treatments are relatively short-lived since the pits or indentations are prone to silt-in within a few years.

In southwestern U.S. where seedling establishment has been a major objective of pitting, pit construction has followed a little different design. In the small conventional-type pits, water accumulation has often prevented seedling establishment (Frost and Hamilton, 1965). To overcome this problem fan-shaped pits or basins were constructed which allowed for a gradation of elevations from pit bottom to ground surface over a distance of 1.8 to 2.4 m. During dry years, soil water and seedling establishment are limited to the lowest portion of the pits, and during wet years when water is excessive at the lower depths, seedlings establish at some higher elevation along the sloping pit bottom. Fan-shaped basin pits can be constructed by attaching an eccentrically mounted wheel that raises and lowers a dozer blade at desired intervals. Similar to the fan-shaped basin pits described by Frost and Hamilton (1965) are the intermediate pits described by Slayback and Renney (1972). They found that intermediate pits were more effective for establishment of grasses than either conventional pits or the larger basin pits. The most recent innovation in basin pitting as described by Abernathy and Herbel (1973) root plows, forms basin pits, seeds, and covers the seeded pits with the root-plowed brush all in one operation.

Vallentine (1971) noted that pits can also be made with a lister-type furrower by raising and lowering shovels at desired intervals. This method of pitting offers a wide selection of pit widths, depths, and spacings but requires more horsepower than conventional disk-type pitters.

The effects of pitting on rangeland watersheds are similar to contour furrowing, but not as extensive. Barnes (1950) reported water-holding capacity of conventional pits

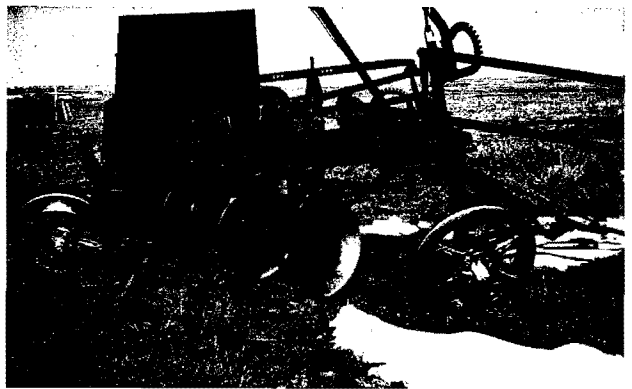


Figure 4. Pitter showing modified disks on the one-way plow (Wight and White, 1974).

were about 7 mm. On pitted ranges, 5 years after treatment, water intake was almost four times as fast as on nonpitted range (Rauzi, 1962), but after 10 years no significant differences were noted (Rauzi, 1968). Ryerson et al. (1970) reported increases in stored soil water of up to 5.3 cm due to pitting when precipitation was above average during late winter and early spring. However, under droughty conditions during this period, pitting had no beneficial effect on stored soil water. Houston et al. (1965) also reported improved soil water conditions under pitting treatments. However, Wight and White (1974) found no measurable differences in soil water content between pitted and nonpitted treatments on a sandy upland range site.

Basin pits have effectively improved soil water regimes. Abernathy and Herbel (1973) found that at the 5-cm depth soil water tensions remained between 1 and 15 atmospheres for 33, 25, and 16 days at sampling points 15 cm and 91 cm from pit bottoms and on adjacent untreated areas, respectively. These data help explain the favorable responses in terms of seedling establishments obtained by basin pitting treatments.

Beneficial effects of pitting treatments on forage production are similar to those ascribed to contour furrowing: (1) improved soil water regime, (2) improved species composition, and (3) improved soil fertility. In the northern Great Plains, pitting has increased forage production about 30 to 50 percent (Valentine, 1971). Pitting has been especially effective on clubmoss-infested sites both as a result of increased soil water and improved species composition. In northcentral Montana, pitting reduced clubmoss cover 25 to 70 percent and significantly increased the ground cover of perennial grasses and sedges. In southeastern Wyoming, Barnes (1950) reported that pitting increased sheep carrying capacity by about 32 percent and lamb gains by about 11 kg/ha/year. He attributed most of the beneficial effects to an increase in midgrasses, primarily western wheatgrass, plus an increase in soil water. He also noted that without western wheatgrass or with relatively pure stands of western wheatgrass, benefits from pitting were small (Barnes, 1952).

Economic analysis of this land-surface modification treatment is difficult because of wide fluctuations in cost input and output values. However, Myles (1974) discussed the economics of rangeland pitting in Colorado in 1974. He reported costs of \$4.90 to \$8.60/ha and concluded that range pitting should be applied selectively on sites with greatest potential for response including off-site benefits like reduced runoff and flood damage. He also noted that rangeland pitting is widely used and is increasing in popularity as evidenced by the fact that almost 100,000 ha of pitted rangeland in Colorado have been cost-shared by the Soil Conservation Service in recent years. Economics of pitting treatments is also tied to treatment longevity. In southeastern Wyoming, Rauzi et al. (1962) suggested that

ranges be repitted every 10 years. However, pitting treatments on dense clay or clayey sites that become very loose on the surface due to freezing and thawing tend to silt-in and are relatively short lived (Nichols, 1969).

### Gully Plugs

Gully plugs as described by Wein and West (1973) are surface modification treatments applied to reduce runoff and erosion. They consist of small dams across microdrainages constructed with a bulldozer by pushing soil down-slope, and vary from 30 to 64 m<sup>2</sup> in area with 0.5- to 0.9-m depths. In the treated area described by Wein and West (1973), they average from 4 to 9/ha. For long-term erosion control or increasing forage production, they have generally been ineffective (Workman and Keith, 1974).

### Ripping and Chiseling

Ripping or deep chiseling treatments are not generally applied for land surface modification. The main objective of these treatments has been to shatter or break up compacting soil layers that inhibit root growth and development. A more moderate version of ripping or chiseling treatments is frequently applied by ranchers or farmers with small farm tractors for renovating sodbound pastures, particularly crested wheatgrass. Used in this capacity, the main beneficial effect has been improved soil fertility associated with the mechanical disturbances. However, ripping treatments applied with large rippers, like the Jayhawk Soilsaver described by Dortignac and Hickey (1963), do substantially modify land surfaces. This implement rips narrow furrows 61 to 76 cm deep and requires the equivalent of a D-8 tractor to pull it. A rotating auger behind each chisel creates a channel about 30 cm in diameter near the bottom of each furrow. Ripped furrows increase the area of absorption of water into the soil. By 1963, an estimated 12,000 ha of public domain in New Mexico had been treated with a Jayhawk Soilsaver.

There have been several reports of beneficial response to ripping treatments. Dortignac and Hickly (1963) reported a decrease in surface runoff the first and third year after treatment of 97 and 83 percent, respectively; erosion was reduced 86 to 30 percent, respectively. They concluded that ripping effectively reduced surface runoff and erosion on deteriorated rangelands with fine-textured soils in New Mexico. However, they found no significant improvement in native vegetational cover during the 3-year period. A later examination of these ripped plots revealed the formation of subterranean channels through which below surface runoff was occurring (Branson et al., 1966). Ripping treatments applied in New Mexico in 1963 were evaluated over a 15-year period by Aldon and Garcia (1972). In this study, treatments were applied with a ripper similar to the Jayhawk Soilsaver but modified with a triangular plate or wing near the top and on each side of the ripper blade to create a small furrow at the surface of each rip. They concluded that while the beneficial effects

on runoff were relatively short, improved forage production patterns may persist for as long as 10 years on ripped areas. Branson et al. (1966) reported that the favorable results obtained with the winged ripper compared with those obtained with the unmodified ripper, "support the view that soil surface, not subsoil, must be modified if conservation practices such as these are to be effective in retaining water and sediment and increasing forage production." Working in Arizona, Branson et al. (1966) found 60 percent higher forage production on ripped as compared with nonripped areas 24 years after treatment and concluded that treatment effects were due primarily to a persistent surface furrow and would persist for many more years. As summarized by Vallentine (1971), effectiveness and longevity of ripping treatments were closely associated with the magnitude of the ripped furrow and concluded that only areas with a hardpan, but otherwise high forage production potential, justify the use of soil-ripping equipment.

### Contour Trenching

Contour trenching is a land-surface modification treatment developed in the 1930's by the Forest Service to reduce surface runoff and subsequent erosion, sedimentation, and flooding conditions. As described by Noble (1963), contour trenching is a precision-type job that requires careful analysis of the site proposed for treatment and careful construction. This surface modification treatment has been used exclusively in mountain terrain on 30 to 70 percent slopes. The contour trench system consists of a series of zero grade in-sloping trenches with size and spacing designed to accommodate a predetermined amount of surface runoff. Trenches may be 1 m or more deep and wide with intrafurrow dams constructed at about 11 m intervals. Treated areas must have a sufficient amount of soil above bedrock to permit construction of the furrows—normally 61 to 76 cm are adequate. The objective of contour trenching is to retain runoff until it infiltrates the soil. Construction of furrows require crawler-type tractors.

There have been few quantitative evaluations of contour trenching effectiveness. However, Noble (1963) concluded that while not a panacea for all flood source areas, contour trenching has proved effective in controlling flooding from badly deteriorated land subjected to high intensity summer rainstorms. DeByle (1970) studied the effects of contour trenches on the east slopes of the Sierra Nevada. He concluded that approximately 177 km of contour trenches in a 41 km<sup>2</sup> watershed may have reduced flow during a flood period by about 74,000 m<sup>3</sup>. Doty (1970) studied the influence of contour trenching on snow accumulation. He concluded that trenches on exposed slopes where snow was redistributed by wind increased snow accumulation but that the associated increase in water yield was insignificant.

### FERTILIZATION

While not a land-surface modification treatment, fertilization is often used with such treatments to take advantage of the increased soil water. Fertilization also significantly affects soil water recharge (Wight and Black, 1972). Fertilization, particularly with nitrogen, stimulates root growth which increases water extraction. Drier soil profiles have more volume for recharge and tend to recharge more efficiently over winter than wetter ones. Also, the stimulated top growth associated with fertilization treatments sometimes provides more crop residue for trapping snow and reducing evaporation.

### LAND SURFACE MODIFICATION AND DISTURBED AREA RECLAMATION

In an industrial age like ours, demands for energy and minerals are high and ever increasing. Extracting fossil fuels and minerals from the earth and building and maintaining roads disturbs several thousand hectares of watershed annually. Until recently, there has been little reclamation and stabilization of these disturbed areas. Now with public reaction, and perhaps overreaction, laws are being written, often without adequate information, specifying mining and reclamation standards. In the following few paragraphs, I will attempt to show the scope of disturbed area reclamation problems for Montana, a state with significant coal reserves, and discuss the use of land surface modifications as reclamation treatments.

Montana includes approximately 38 million ha of which 83 percent are classified as a forest-range complex. Surface mineable coal reserves are estimated at 29 billion metric tons and underlay a land area of about 570,000 (Northern Great Plains Resources Program Staff, 1974). In 1974, approximately 13 million metric tons of coal were surface mined from 129 ha (Montana State Department of Lands, unpublished data). Projected annual mining rates by 1980 is 44 million metric tons from 455 ha.

Roads and road rights-of-way in the state cover about 570,000 ha or an area equal to the total surface mineable area (Robert Champion, personal communication). Supplying gravel and fill material to construct these roads have disturbed an additional 60,000 to 95,000 ha. Completion of the State's 1,900-km interstate highway system will disturb approximately 17,000 ha of which about 12,000 ha not covered by asphalt will need reclamation treatments.

Land disturbances by road construction and surface mining affect the hydrologic cycle in many ways. Natural drainages are often disrupted causing water shortages in one area and excesses in another. Subsurface water movement can also be disrupted resulting in changes of groundwater supplies. Roadside cuts and spoil banks from surface mining may have high runoff rates and the associated problems of sedimentation. Contamination of

both runoff and groundwater supplies with excess salts or other toxic minerals is another possible watershed problem associated with surface-mine reclamation.

Most of the disturbed land reclamation in Montana has been associated with road construction; and runoff reduction and soil stabilization are accomplished by establishing and maintaining a vegetational cover on disturbed sites. Replacing topsoil, hydroseeding, and mulching are the major tools used in revegetation. Recently, most land surface modification research on disturbed areas has been done in conjunction with surface-mine reclamation (Hodder, 1973; Sindelar, 1974). Effective land modification treatments include: (1) pitting, (2) chiseling, (3) gouging, and (4) dozer basins. The pitting and chiseling treatments are similar to previously described eccentric disk pitting and deep chiseling. Gouging is done with a specially designed implement which forms elongated basins approximately 30 to 40 cm wide, 10 to 30 cm long, and 15 to 20 cm deep. Dozer basins are elongated basins 3 to 5 m long and 0.6 to 1.0 m deep formed on the contour with a bulldozer blade or a specially designed blade attached behind the bulldozer. All treatments improved the soil water regime through the processes of snow trapping and reduction of snowmelt and rainfall runoff, and provided hospitable environments for seedling establishment. A good vegetational cover was established with all treatments with the gouging treatment judged best. The second year after establishment, production of seeded grasses averaged over 1,300 kg/ha on the chiseled, gouged, and dozer basin treatments while nearby native range yielded less than 800 kg/ha of native grasses (Sindelar, 1974). In these studies, the exotic grasses and legumes were established more readily than most of the native grasses.

On mining sites, where the overburden is relatively free of salts and other toxic elements and there are no major textural problems, revegetation and stabilization can be readily accomplished by leveling the spoil banks to workable grades and using treatments like gouging or pitting to provide favorable soil water environments for seedling establishment. Fertilization, especially where topsoil has not been replaced, is recommended, and sometimes is essential.

### SUMMARY

Past research has shown that land-surface modification treatments can effectively reduce runoff and erosion and increase soil water and subsequent forage production on arid and semiarid rangelands. The treatments are not currently being used to their full potential as watershed management tools because of several factors: (1) unstable economics for treatment costs and product values; (2) need for specialized equipment—treatments that can be applied by individual ranchers and farmers have been the most popular; (3) landowners' unfavorable attitude toward the rough microtopography associated with the treatments;

and (4) professional resource managers' (including game and wildlife managers) unfavorable attitudes toward perturbation of native ecosystems. Land-surface modification treatments can play a vital role in meeting the forage demands of an ever-expanding livestock industry especially when utilized in combination with introduced species and fertilization. Research should be continued on the development and evaluation of land-surface modification treatments with emphasis on reducing application costs and increasing treatment longevity.

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# Watershed Management: State of the Practice Precipitation Modifications

*Phillip E. Farnes\**

This paper discusses snow management, weather modification, and lightning control.

## SNOW MANAGEMENT

Since many of you may not be familiar with the snow survey program in the United States, I would like to briefly describe this activity. Snow surveys had their beginning near Reno, Nevada, in the early 1900's with Dr. James E. Church. His early attempts to correlate snowpack in the Sierra Nevada Mountains with fluctuations in levels of Lake Tahoe is the basis for today's work in the Cooperative Federal, State, and Private Snow Survey Program. Since its beginning, the snow survey program has provided the basic data for forecasting water supplies for agricultural, municipal, and industrial uses so that the snowmelt-generated water could be better managed. Until recently, observations of snowpack were made only on snow depth and water content at designated locations called snow courses. Today snow surveys have evolved into a data-gathering program which encompasses collecting information on total precipitation, temperature, wind, radiation, relative humidity, snow density profiles, and total snowfall in addition to snow depth and water content (Soil Conservation Service, 1972). This information has been found necessary for refining forecast procedures to provide more accurate and timely estimates of water supplies that can be used by water managers and water users.

Other groups, however, are requesting climatological and hydrological information from the mountainous west to facilitate planning for future growth and development. To gather data more efficiently to meet these ever expanding needs, a revolution in methods and equipment has been required. While still relying on parties of snow surveyors using standard snow sampling equipment to gather basic snow data in the mountains, the program has tested and installed new, sophisticated systems to sense, record, and reduce hydrologically important parameters from remote mountain sites.

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Since the West-Wide Cooperative Snow Survey Program began in the early 1930's snow course sites have grown to more than 1,900 in the Western United States. These continue to be the backbone of the Cooperative Snow Survey Program. Snow course readings are generally taken three times a year: March 1, April 1, and May 1. Additional early- and late-season measurements are made at key locations. In southern states, more early-season snow surveys are taken since the maximum snow accumulation period is usually reached about a month before that in more northern states. Snow pillows—butyl or metal containers usually having an area of about 7 m<sup>2</sup> and 5 cm thick which weigh the water equivalent of the snowpack—were introduced to obtain a complete picture of snowpack accumulation and depletion. Presently there are about 157 snow pillows installed and operating in the Western United States.

Storage precipitation gages have been installed to obtain year-round data at snow course and snow pillow sites to better define the annual precipitation regime and effects of rain on snow events. Some 400 precipitation gages are operating in this network at present. Recording precipitation gages as well as snow pillows yield data on storm intensity and duration in mountainous areas that can be interpreted and applied to management of the mountain snowpack and subsequent runoff.

Using thermographs at the remote sites gives information from which melt rates can accurately be calculated. Wind run provides data to help compute snowpack depletion due to evaporation and sublimation. Soil moisture stations at 140 selected locations provide information on basin wetness that directly affects both surface runoff and groundwater recharge. Soil temperature at these sites provides data on whether soils are frozen or not. Temperature information is also useful in the classification of soils.

Isotopic profiling snow gages allow snow hydrologists to study snowpack stratigraphy in detail. These instruments measure snow density at increments as small as 1 cm. Snowpack accumulation, metamorphism, and deple-

tion and rain on snow events can now be studied via this *in situ* measurement technique.

Further advances in the field of snow surveys were made when many of the above mentioned parameters were adapted to being read directly into a radio telemetry system at the remote sites. Data became available on a real-time basis at a base station. Here the data are received, recorded, and reduced with the help of computer technology.

The Soil Conservation Service is presently modernizing its data gathering and processing function by implementing a SNOTEL system in the Western United States. SNOTEL is a acronym for Snow Survey Telemetry. This hydrologic data system transmits readings from more than 500 remote data sites throughout the Western United States to a central computer processing facility using meteor-burst communication methods. Data on parameters such as snow-water equivalent, precipitation, temperature, and others such as wind, humidity, and radiation are received and stored for use by SCS and other cooperators in water supply forecasting, flood warning, avalanche warning, recreation planning, area accessibility, basin modeling, fire weather data, and other snow management or snow-related studies.

By correlating streamflow volumes with snow-water equivalent readings and other variables such as spring precipitation and soil moisture indexes, relatively accurate runoff forecast equations can be developed. Inclusion of current data into these forecast equations provides estimates of the streamflow that will be generated when the current season's snowpack melts. These forecasts are used by many different groups and agencies. Farmers and ranchers who obtain their irrigation water supply from natural streamflow can plan their cropping and irrigation according to the water supply forecasts. Reservoir operators use forecasts to determine filling rates and reservoir outflow (Farnes, 1973). For multiple use reservoirs, the water supply forecasts are used to allocate storage volumes to flood control, irrigation, power generation, recreation, and other uses. Often, single-purpose irrigation reservoirs have been operated so as to reduce flood flows or to provide water for recreation, fish and wildlife, and other beneficial uses by considering the water supply forecasts in their reservoir operating plan. In the Western United States, the water supply forecasts are an integral part of the springtime flood control operations. It is only through this advance knowledge of the ensuing runoff that reservoirs can be emptied to handle large spring runoffs from a heavy snowpack or can be kept closer to full in years when the mountain snowpack is below average. In years of shallow snowpack, farmers have reduced their acreage planted because they know they will not have adequate water supply for their entire irrigation season.

The information obtained from snow surveys is also being used for other management decisions. There is a

very high correlation between average seasonal snowpack and average annual precipitation. This relationship has been used to develop relatively accurate isohyetal maps for the mountainous areas of Montana (Farnes, 1972, and Soil Conservation Service, 1974). Snow survey data have also been used to develop maps showing maximum annual snowwater equivalent, average annual snowfall, (Soil Conservation Service, 1974) 50-year frequency ground snowloads, and areas having adequate snow for potential alpine ski areas and for winter sports recreation areas (Farnes, 1971, and Soil Conservation Service, 1969). Snow-water equivalent and annual precipitation are important parameters for estimating streamflow yields from ungaged watersheds (Soil Conservation Service, 1971). Snow-water equivalent maps can also be used to calculate realistic increases that may be generated by weather modification activities. Snowfall information is an important parameter for estimating snow removal costs for design and location of major transportation systems or for new subdivisions and housing areas where snow removal may be required (George and McAndrew, 1973, and Vance and Whaley, 1971). Data on total snowfall is important in the planning and design of water-spreading irrigation systems in the Northern Great Plains where significant runoff comes from snowmelt on frozen soils prior to the main growing season. Snowfall is also necessary for ski, snowmobile, and winter recreation areas. Accurate information on snowfall substantially reduces the risk of investors and developers and enables them to better manage their operations.

Snowload information is extremely valuable to those designing and building structures in snowy areas. In mountain areas, the snowloads are substantially larger than those commonly experienced in the habited valley areas. These loads must be incorporated in the design and construction of buildings if they are to withstand the weight of the heavy snow buildup. Accurate snowload data permits adequate design to prevent building collapse without over-designing the structures and thereby increasing costs.

The above mentioned uses to which snow data are being used for snow management is certainly not complete. Other studies include relating snow and precipitation distribution to fish and wildlife populations, developing watershed simulation models to evaluate effects of land use change, predicting avalanche potential, evaluating water balance studies, developing regional inventories of water resources, planning water supply for large scale coal and oil shale developments, studying climatic shifts and trends, evaluating vegetation manipulation and obtaining ground-truth data for satellite imagery (Weisbecker, 1974).

A vast amount of data has been collected in the snow survey program for the expressed purpose of forecasting water supply. Additional interpretations of data collected in this program are now being made to aid planners, architects, engineers, conservationists, managers, and developers in making rational land use and investment decisions. A substantial degree of uncertainty has been

removed from the planning process as a direct result of such interpretation.

In addition to managing the runoff from a snowpack, there has been some research on the management and manipulation of snow in areas of strong winds and sparse timber. Most of this research has been with snow fences. At any site where snow fences are being considered, a careful evaluation should be made of actual benefits derived from the water being produced in relation to the cost of installing and maintaining the fences and the visual impact. In the future, it may be possible under certain small-scale situations to use snow fences as an economical method for generating additional water supplies. For many years, snow fences have been used along highways and in residential areas to induce drifting behind the fences and reduce the amount of snow reaching the roadways. Some research has been directed toward using fences and deflectors to reduce snow cornice buildup on mountain ridges. Structural barricades have been installed in known avalanche paths to prevent snow releases. Structural diversions have also been tried in some avalanche paths to deflect or divert avalanches after they release.

Entrapment of snow by grass barriers is being researched in the Northern Great Plains. The additional moisture being added to the soil profile may be sufficient to allow annual cropping in areas where alternate fallow and crop are now being used. For many years, windbreaks from trees have been used to modify snow accumulation and windflow around farmsteads in the Great Plains.

There has been some research on retardants to delay melt and on chemicals to delay or speed up melt. Reduced evaporation from the snow surface may have some practical application in water-deficient areas where value of water saved is sufficient to warrant additional cost for applying the evaporation retardant.

There are situations where man has inadvertently modified the snowpack. One of these is logging. In the cold climates of the northern Rocky Mountains are large areas of fire-generated lodgepole timber stands. Clearcutting is currently the standard method for harvesting this timber. The snowpack is substantially increased in these clearcut areas and streamflow from these clearcuts is also increased. This is contrary to some research findings; however, records that we have obtained in the past 10 years indicate that in southwest Montana, clearcutting of the dense lodgepole timber stands does result in an increase in the water produced from these areas.

### WEATHER MODIFICATION

It should be understood that my field of expertise is not weather modification. In my occupation of forecasting streamflow from snowed areas, it is necessary to be familiar with weather modification activities so that any increase in precipitation may be incorporated in the water

supply forecasts. The following information has been obtained from various reports on weather modification and through association with other scientists (Hess, 1974).

There have been many attempts at weather modification throughout the world. The first written weather modification proposals date back to the early 1900's. Since then, there have been numerous documented reports and proposals to increase precipitation. The first scientific weather modification occurred in 1946 when Langmuir and Schaefer used dry ice to produce snow crystals in the laboratory. Today silver iodide is commonly used in weather modification work. Extensive research and work in weather modification activities, particularly that directed toward increasing precipitation, has followed the early scientific findings of Schaefer and Langmuir. Many private contractors have entered the field of weather modification, particularly in California. Most areas of the United States have experienced some form of weather modification in recent years.

Today there are many federal and state agencies, private utilities, and universities involved in extensive research of weather modification (Weisbecker, 1974).

My personal experience with weather modification activities indicates that you need to know who is doing the research and who is writing the report in order to ascertain effectiveness of weather modification. I suggest that reports of weather modification be reviewed carefully to determine the technical competence of those performing the research and writing the report before accepting claims of increased precipitation.

In some mountainous areas, there are logistic problems associated with locating silver iodide generators. The large number of temperature inversions that exist in many mountainous areas almost preclude obtaining any significant increase in precipitation when ground-based generators are used. Generators on mountain peaks are difficult to operate and maintain in these severe climates. Airborne generators increase operation costs. It is extremely difficult with currently available instruments to accurately monitor precipitation increases. Many of the instruments that are currently being used to measure precipitation are not sufficiently accurate to measure the increment of increased precipitation that may be expected from modification. The natural variation of precipitation over small areas and from year to year and storm to storm is substantial and further complicates the accuracy of monitoring precipitation. There is extensive work now being conducted in the United States to obtain a true evaluation of weather modification activities (Weisbecker, 1974). Within a few years, it is hoped, it will be possible to accurately predict when and where to seed, how much increase can be expected, and what other side effects may result.

The weather modification to increase precipitation appears to have the greatest potential in the seeding of orographic storms during the winter months. Increases in precipitation in the magnitude of 10 to 15 percent are commonly referred to when discussing seeding of orographic storms passing over mountain barriers. The greatest effort in research of weather modification has been directed toward seeding of winter orographic storms.

Presently there is extensive research being carried on in the Colorado River Basin to determine and refine the effects of orographic seeding operations as well as evaluate many possible side effects (Weisbecker, 1974).

Most weather modification activities have been directed toward providing additional water supply (Montana State University, 1972). However, in many situations where storage is not available, the problem may not necessarily be a water shortage but rather a poor seasonal water distribution. In snowmelt areas, flows during late summer, fall, and winter may be quite low, increasing to large flows during the main snowmelt period. A 10- to 15-percent increase in snowpack in the mountainous areas may not significantly increase the late season water supply. From snow survey records, it has been determined that normal melt rates average approximately 2.5 cm snow-water equivalent per day with 4 cm melt possible on relatively warm days. Under certain climatic conditions, larger melt rates are possible. Many mountain areas of the Western United States accumulate normal snowpack of 50 to 75 cm of snow-water equivalent during a winter season. An increase of 10 percent would be an additional 5 to 7.5 cm of snow-water equivalent. This incremental increase will melt in 2 to 3 days. Therefore, this additional water does not lengthen the streamflow hydrograph to any significant extent. To modify this variable, seasonal streamflow may require the construction of a reservoir whereby large snowmelt streamflows can be stored in the reservoir and released later when the natural runoff is much lower. If reservoirs are constructed in these drainages, then weather modification for additional water supply may not be necessary. However, when the basins have become fully developed and the entire water supply is controlled and is being used, then additional increases in the mountain snowpack by weather modification may prove to be beneficial.

Irrigation is one of the largest consumptive uses of our water supplies in the Western United States. Further compounding the large need for irrigation is poor irrigation efficiencies. In many areas, irrigation efficiencies of 10 to 15 percent are common. To date, little has been done in the legislative area to require more efficient water use since it is politically disastrous to advocate changes in water law. Water rights were established very early in the settlement of the western lands and have been preserved by law ever since. It is commonly expressed "that you have a better chance remaining alive if you steal a man's wife than if you steal his water."

Not much improvement is seen in increasing these irrigation efficiencies until such a time that it becomes economically feasible for the farmer or rancher to improve his efficiency or until such time as the legislative segment receives enough pressure to require improved efficiencies through enforceable laws.

One problem that deserves more attention when considering increased snowpack and streamflow is the associated increases in sediment production. The impact of additional sediment may overshadow the benefits of increased runoff. Work being done in mountain watersheds shows a high correlation between streamflow volumes and sediment production and indicates a major portion of sediment comes from bank erosion. Therefore, the higher the streamflow, the larger the volume of sediment being transported. The increased runoff yields that are or may be generated from logging activities and weather modification have not fully considered the implications of changes in sediment production resulting from these actions.

Another problem associated with weather modification and increased precipitation is saline seep (Fogarty, 1974). Certain areas have geologic conditions where excessive moisture passing through the root zone can saturate the underground zone bringing undesirable salt solutions to the surface. The salts that remain when the moisture evaporates ruins the land for agricultural purposes. This problem exists throughout the Great Plains area of the United States and Canada and is aggravated by some farming practices. Strip farming was initiated in the drought years of the mid 1930's to conserve moisture. It worked so well that this method of farming has continued. Precipitation in central Montana during the 1930's averaged approximately 25 cm annually, whereas in the early 1970's when the saline seep problem was becoming very critical, the average annual precipitation was approximately 43 cm. Increased precipitation by weather modification without needed changes in cropping patterns will increase the saline seep problem and further remove more land from production in susceptible areas.

The encroachment of trees in mountain meadows has been observed when 4- or 5-year periods of continually above-average annual precipitation occur in the 50- to 75-cm precipitation zone. During alternately drier years, trees cannot survive the drought periods so that these areas remain as mountain meadows. Increased precipitation that would permit survival of the seedling trees could decrease the size of mountain meadow areas (Buchanan, 1972).

Animals also demonstrate dependence on precipitation cycles. The study of eagle nesting areas by a Montana State University researcher indicates that most eagle nests are located near the 500 cm snowfall zone (Baglien, 1975). This is the transition zone where the moisture is sufficient to support abundant plant growth providing food

supply and habitat for large populations of rodents and other animals that in turn provide a food supply for the eagles. Areas at higher elevations have longer winter seasons with shorter growing seasons and fewer rodents. Some older eagle nests were observed at higher elevations in this study. From historical snowfall information, it now appears that during drier periods of the 1930's, the 500 cm snowfall zone may have been at a higher elevation and in the vicinity of these abandoned eagle nests. It is a logical assumption that the eagle moved its nesting area to a more suitable environment with the climatic change to a wetter precipitation period. Prior to this study, it had been speculated that the eagles inhabiting these nests had either died or migrated to other areas.

This same situation may exist with various grass species. What may be a dominant vegetation species in a range during a prolonged wet precipitation trend may not necessarily be the same species that is dominant during a prolonged drought period.

There is definitely a need for more research into climatic trends and intercorrelation with other phenomena. Many researchers fail to take into account the variation in climatic conditions when researching in areas that are relative to or affected by long-term precipitation and temperature changes.

Of course, man's occupancy on earth has also caused some weather modifications. As an area is urbanized or farmed, land use changes take place that affect the climate in that vicinity. In the urbanized areas, there is heat output from the exhaust of the automobiles, heat exhaust from air conditioning units, heat from factories, and increased heat from the solar absorption by the streets, roofs, pavements, and parking lots. It has been fairly well documented that there are heat islands within large urban areas. Increased vertical drafts from these heat islands carry pollutants from urbanization and human activity into the atmosphere. In some areas it has been well documented that chemical and photochemical reactions occur from these pollutants. There appears to be increased precipitation downwind from these urban areas. Some studies show that the daily precipitation is greater during the Monday through Friday period than the precipitation that occurs on Saturday or Sunday. The precipitation during the Monday through Friday period is greatest on Friday and the least on Monday. It is theorized that pollutants being added to the atmosphere are providing additional nuclei which in turn results in increased precipitation.

One of the problems associated with the evaluation of any activity that involves "Mother Nature" is her highly variable climatic and weather patterns. People demand increased water supply in drier years and flood protection in wetter years. Long-range precipitation and runoff trends show extreme variations. There does not appear to be any systematic pattern to these trends. The precipita-

tion may be near the maximum of record one year followed by a year of near minimum record followed by another year of near maximum record. This situation was observed in Montana in 1972, 1973, and 1974. Indications are that 1975 may be another year of near maximum precipitation. Drought or wet periods may span 3 to 10 years or may be intermixed with so-called "average" or "normal" years.

Much of our agriculture production is dependent on natural precipitation. Rangeland, timberland, and farmland, including much of the wheat growing areas in the world, are not under irrigation. If we are to continue production of food and fiber for our population, we need to be aware of and make provisions for these variable climatic trends. After a farmer has good crops and fairly wet weather for a period of 5 to 10 years, he begins to expect this situation to continue forever. Looking back through weather records, we can identify periods of extreme drought and periods of floods. The chances are good that these extremes will be observed again in the future.

I have heard that most of the great societies and civilizations in the past did not disappear from the earth because of war or disease but were eliminated because of drought and subsequent famine. Possibly, now is the time to assess our potential for producing enough food and fiber to satisfy population projections during a period of prolonged drought.

There are many social implications involved with weather modification. As with any operation that modifies the natural environment, there are some severe social conflicts arising from weather modification activities (Bonneville Power Administration, 1973). There does not seem to be any particular problem when weather modification is used to dissipate fog over an airport so that airlines can make their scheduled flights. However, when precipitation is increased or attempts are made to increase precipitation over wilderness areas or mountainous areas where it may induce additional avalanches or where additional precipitation may cause damaging floods, the public becomes very concerned and shows up at public meetings in great numbers to testify against such projects.

The general public has many misconceptions about weather modification activities. It is absolutely necessary that the public be kept informed of weather modification plans and that the expected results be honestly appraised by scientists working in this field. Too often, those attempting to sell a project do not explain all the ramifications. Later, when unmentioned or unexplained things happen, hard feelings are created. This may jeopardize or eliminate future projects since people begin to disbelieve the scientist that is providing the interpretations.

Legally, very few weather modification cases from which precedents can be determined have been tried in court. There is still a question as to who has the legal right

to the precipitation that occurs from seeded storms. There are some questions as to who shall receive the benefits, who shall pay the costs, and who shall be responsible for liquidating damages if and when they may be proved in court.

### LIGHTNING CONTROL

Only a limited amount of work has been done in the United States in lightning control (Hess, 1974). Most of the work to date has been done in Region I, U.S. Forest Service, in the Northern Rocky Mountain area of the United States. This operation, called "Project Skyfire," was the first systematic program on lightning control. It was first conducted in western Montana during the summers of 1960 and 1961. Some work continues today. There is additional work in Arizona with chaffing and some research with small rockets to dissipate electrical charges and reduce chances of launched satellites being hit by lightning. It is anticipated that there will be more research into lightning in the future since in the United States in an average year lightning kills about 600 persons and injures about 1,500. The death total attributed to lightning in this country is greater than that for any other severe weather phenomenon including tornadoes and hurricanes. Of course, we all are familiar with the extensive loss due to lightning-caused forest fires. In the United States, the annual cost of controlling these fires approaches \$100 million. Total property losses caused by lightning in the United States can only be estimated but it is believed to be about several hundred million dollars per year.

There has been some research on weather modification to suppress hail. The effort directed toward this has been small. In some of the Great Plains areas of the United States, a few researchers and a few operational projects have addressed the problem of hail reduction to prevent or reduce crop damage. As farm produce becomes more valuable, additional research will undoubtedly be directed toward hail suppression.

Weather modification activities are also being conducted to find methods for decreasing severity of hurricanes and tornadoes. As time progresses, some of these weather modification activities may have more value or benefit to society than those directed toward increasing precipitation.

### SUMMARY

There are many activities being carried on in the fields of snow management and weather and lightning modification in the United States.

Increasing population with added new demands on water supply are requiring changes in water management practices. The world's water supply is limited. It is only through improved management of our present supply and a better knowledge of climatic variations that we can hope

to meet the increasing demands for water. Future research in these areas must be intensified or some substitute discovered that will replace water.

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# A Review of Cloud Seeding in Australia and its Potential Impact on Water Resources Management

B. Watson\*

## INTRODUCTION

The first man-made rain ever to reach the ground did so in Australia in February 1947, as a result of research by the Commonwealth Scientific and Industrial Research Organization (C.S.I.R.O.). The research into the rain process and its modification has continued since that date, initially within the C.S.I.R.O. Division of Radiophysics and more recently within the C.S.I.R.O. Division of Cloud Physics.

Twenty-eight years of research into cloud physics and weather modification has brought rainmaking to the stage where increases in rainfall are economical in certain regions of Australia. This is particularly so in the catchments of the Hydro-Electric Commission in Tasmania.

The salient features of the current research into cloud physics and cloud seeding in Australia are reviewed, its operational application, and details of the work in Tasmania are presented. The potential implication on watershed management and power generation is discussed.

## FORMATION OF CLOUDS

Clouds develop when either columns of warm humid air rise and cool to form cumulus type cloud, or when two air masses converge to form layered stratiform clouds. The moist air cools and increases in humidity until it becomes saturated and water condenses on tiny particles known as "cloud nuclei." These minute drops must then grow more than a million times their original volume to form rain drops, often by colliding with one another by a process known as coalescence.

Another process occurs when the water droplets rise to levels where they become supercooled, often at temperatures as low as  $-15^{\circ}\text{C}$ . They only freeze in the presence of particles known as "ice nuclei," to form ice crystals, then snowflakes which melt to form rain.

Silver iodide smoke provides very effective artificial ice nuclei which can rectify any natural deficit.

## CURRENT CLOUD PHYSICS RESEARCH ACTIVITY IN AUSTRALIA

Smith (1967, 1974) reviewed the state of the art of cloud seeding in Australia and in 1973 the C.S.I.R.O. Division of Cloud Physics published a review of its research activities which are summarized below to show the scope and nature of the work being carried out:

- (i) The Macrophysical Properties of Clouds  
Cloud formation, cloud dynamics—Field data are being collected using a DC3 aircraft equipped as a flying laboratory.  
Cloud models—More elaborate, three dimensional models are required and the observational data will play an important part in proving the models.
- (ii) Condensation Nuclei and Cloud Droplet Formation  
Condensation first takes place on soluble particles and the number activated depends on their size spectrum, their chemical composition and cooling rate.  
Clouds formed in air masses rich in nuclei have high concentrations of smaller drops. Most active cloud nuclei are small particles of ammonium sulphate which have a life of one day and it is suspected they are formed *in situ* from gases in the atmosphere.
- (iii) The Growth of Cloud Droplets by Condensation and Coalescence.

The early stages of droplet growth where condensation dominates in convective clouds is now well understood. A major aim of future work is to develop equipment and to make observations of the growth to raindrop size by coalescence and collision in natural clouds.

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## (iv) Ice Nuclei.

Methods have been developed for measuring ice nuclei concentrations which aid in the formation of ice crystals and hence growth of raindrops in cold clouds. Measurements taken throughout the world indicate that the atmosphere tends to have a deficiency in natural ice nuclei. Future work aimed at improving measuring techniques, making airborne measurements to identify the nature and origin of the nuclei.

## (v) Studies of the Properties of Mixed Clouds.

Sampling techniques have been developed for ice crystals and water drops in clouds.

Large concentrations of ice crystals have been found in cumuli which exceeded ice nuclei concentrations.

Extensive measurements through strato-cumulus showed similar concentrations of both ice nuclei and crystals.

## (vi) Cloud Seeding

The results of the laboratory experiments and theory are being tested in the field to increase the rainfall.

## (a) Seeding single clouds.

Experiments are being conducted into top seeding clouds using pyrotechnics impregnated with silver iodide, and also dry ice. Sophisticated methods are being used for taking observations including improved rain-drop impactors and radar.

Experiments in Queensland have been initiated which at this stage show that suitable clouds appear reasonably often and seem to react favorably to seeding. Randomized trails of single cloud seeding have commenced.

## (b) Seeding over large areas.

The results from a 4 year experiment in Tasmania are being analyzed in cooperation with the C.S.I.R.O.'s Division of Mathematical Statistics. Preliminary results show no effect in spring and summer but during autumn and winter there was an increase of 15 percent to 20 percent at a very satisfactory level of statistical significance.

Detailed evaluations are still being made but initial indications are that the best conditions for seeding involve stratiform clouds and days with moderate natural rain.

More efficient methods for experimental design are being developed.

## (c) Future experiments.

Smith (1974) suggested the following avenues for future experiments:

Favorable areas should be tested for the effects of releasing silver iodide smoke from the ground as well as from aircraft. Continued work with pyrotechnics and dry ice to develop effective methodology. Utilization of computer modeling for evaluation purposes. Experimental work with clouds which do not reach up to freezing level (hence no ice crystal formation).

## (vii) Particles in the Stratosphere.

Balloons are being used to sample particles in the atmosphere as a whole, in cooperation with similar programs in the northern hemisphere. Methods have been developed which aid in determining their chemical nature.

### CLLOUD SEEDING EXPERIMENTS OVER LARGE AREAS

Several area experiments have been conducted in Australia by the C.S.I.R.O. and these are listed in Appendix A, together with the references to the Annual Reports issued by the C.S.I.R.O. These have been effectively summarized by Smith (1967).

The early experiments (prior to the Tasmanian experiment) proved difficult to evaluate due to the following limitations which emerged:

Results deteriorated with time.

Seeding appeared to increase variability resulting in increases as well as decreases.

Rainfall gradients varied more than expected.

Cloud observations were limited to target area only.

The Tasmanian experiment was designed to overcome the defects inherent in the earlier experiments. This experiment, the results and associated developments, are dealt with more fully in following sections.

After 16 years activity in area cloud seeding the position may be summarized along the following lines (Smith, 1967, 1974), (C.S.I.R.O., 1973):

(a) Seeding may either increase or decrease the rain and not necessarily only in the desired area.

(b) In selected climates, seeding clouds with silver iodide has substantial effects on the rain over an area.

(c) Careful planning and execution is required to measure the effects.



- (d) Drought-breaking on a large scale is not possible by cloud seeding in the conditions so far encountered.
- (e) Estimating the prior effect of cloud seeding in a particular region is not feasible.
- (f) There is a need for new ways to assess the results of cloud-seeding operations in a reasonable time.

### CLOUD SEEDING OPERATIONS IN AUSTRALIA

The legal position in Australia defines that the responsibility for attempts to alter the weather rests with the State Governments rather than the Commonwealth Government, and at present there are no operational cloud seeding programs being funded by any of the State Governments.

The C.S.I.R.O. introduced the results of their research to State Government officers by providing technical training courses and as a result programs were implemented in South Australia, Victoria, Queensland, Western Australia and New South Wales, and by the Hydro-Electric Commission in Tasmania (Appendix B), (Mahon, Adderley et al., 1970).

Generally there is little published information available on the various state ventures, probably because the operations have been carried out to optimize the rainfall without randomization or controls and the information cannot be used for accurate evaluation. Thus, results have not been published.

#### Victoria

Seeding was carried out from 1966 to 1970. An initial appearance of spectacular down-wind effects (Adderley and Bigg, 1971) soon disappeared: as usual reliable assessment of the uncontrolled operation was not possible.

Annual Budget was about \$100,000.

#### New South Wales

All of the early seeding (prior to 1969) was for drought relief. A project was commenced in 1969 to seed continuously in an attempt to increase production and to prolong the favorable seasons in semi-arid New South Wales (Mahon, Adderley et al., 1970).

#### Tasmania

The operations in Tasmania are covered in detail in Cloud Seeding Experiments section.

In general the lack of activity in the states since 1970 probably stems from a combination of the following factors:

(a) The state of our theoretical knowledge and inability to predict with some certainty the effect of seeding in advance (e.g. it is not possible to predict the frequency of occurrence of particular cloud conditions).

(b) The conservative attitude of State Governments and officers reflected in the tendency for spasmodic last minute drought relief measures.

(c) The impossibility of proving the outcome of the operations without sophisticated equipment, design, and long duration.

(d) Initial disappointment that seeding is not a miracle cure for droughts.

(e) State of the economy—particularly in the rural sector.

(f) Favorable weather conditions during recent years.

(g) Investment alternatives that increase the efficiency of existing water supplies.

### CLOUD SEEDING EXPERIMENTS IN TASMANIA

#### Experiment Stage 1 — 1964-1970

As described by Smith, Adderley, Vietch, and Turton (1971), the C.S.I.R.O. carried out a cloud seeding experiment in Tasmania from 1964 to 1970 inclusive to determine the amount by which seeding clouds with silver iodide smoke released from an aircraft could increase the precipitation over the hydro-electric catchments in the Upper Derwent River Basin.

The target and control areas are shown in Figure 1 and seeding was carried out during alternate years by dividing the time into periods of 10 to 18 days. The periods were arranged in pairs and a random method was used to determine which period out of each pair would be seeded. Clouds were seeded if their tops contained supercooled water at a temperature of  $-5^{\circ}\text{C}$  or colder for stratiform clouds and  $-10^{\circ}\text{C}$  or colder for cumuliform clouds, and if they were deep, "solid" and compact, without excessive included clear-air spaces, and with tops vertically above their bases.

The operational periods were:

1964 : 13.5.65 to 23.12.64  
 1966 : 29.12.65 to 21.12.66  
 1968 : 14.9.67 to 26.2.69  
 1970 : 19.2.70 to 7.12.70

A network of 54 rain gages was used by the Commonwealth Bureau of Meteorology to firstly estimate the daily rainfall for each of the areas, then the rainfall for

each "period" of 10 to 18 days. Rainfall totals for the 4 years were then extracted for each area for seeded (S) and unseeded periods (U):

- Target area (T)
- Western half of target area (TW)
- Eastern half of target area (TE)
- North control area (NC)
- South control area (SC)

Mean East Control area,  $EC = (NC + SC)/2 =$  original control (C)  
 Mean West Control area,  $MWC = (NWC + SC)/2$

The totals were also divided into the seasons of Summer, Autumn, Winter, and Spring.

The results were presented in the form of double ratios (DR) such as T/C (seeded): T/C (unseeded), i.e. the

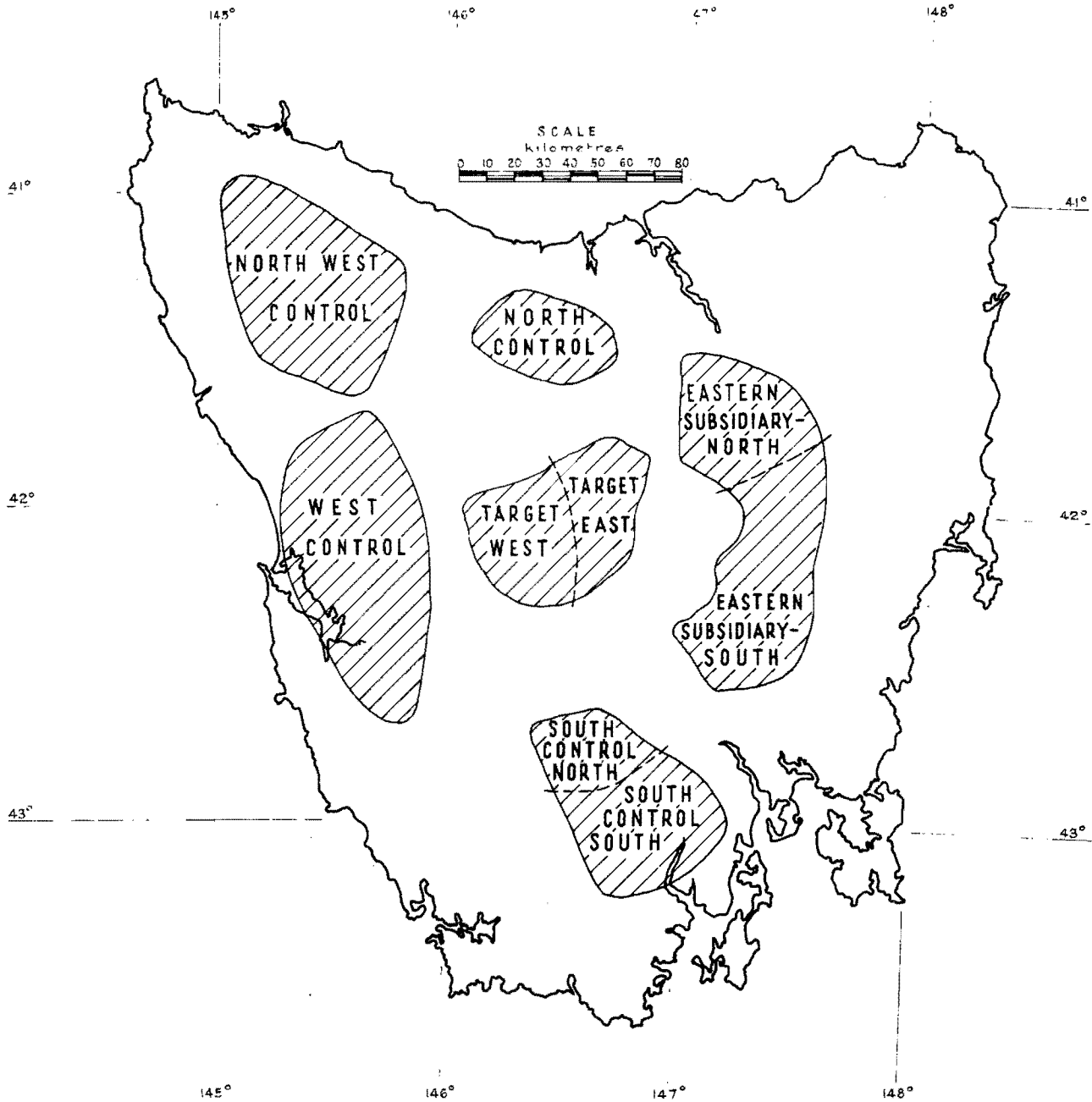


Figure 1. The Hydro Electric Commission of Tasmania cloud seeding experiment, experimental areas.

ratio of the total rainfall in the target area to that in the control area during seeded periods divided by the similar ratio for the unseeded periods. A double ratio value greater than 1 indicates positive effect, equal to 1 zero effect, less than 1 negative effect. A multiple regression analysis was also carried out to predict the period target area rainfalls and calculate the increase factor and significance levels. This work was carried out by the C.S.I.R.O. Division of Mathematical Statistics.

The conclusions were as follows:

- (a) Cloud seeding caused an increase in rainfall of about 15% to 20% in autumn and winter.
- (b) The increase in the eastern half of the target area appears to have occurred in both autumn and winter. Further results are desirable to define the detailed seasonal distribution of effects.
- (c) It is possible that seeding caused a rainfall reduction in the eastern half of the target area in summer but the evidence does not justify a conclusion to that effect. (Smith et al., 1971).

### Experiment Stage 2—1971

On the basis of the above results the Hydro-Electric Commission decided to continue cloud seeding in 1971 and the following is a brief account of the operation and results.

#### *Description*

The object of the second stage of the cloud seeding experiment was to determine the amount by which seeding clouds with silver-iodide smoke released from an aircraft can increase rain over a designated target area. Time was divided into periods of about two weeks and a random process was used by the C.S.I.R.O. Division of Mathematical Statistics to predetermine the periods during which seeding would be carried out. Two out of every three periods were seeded.

The target and control areas are shown in Figure 1 and are essentially the same as those used in Stage 1 of the experiment. The original three areas to the north, north-west, and south of the target area were used as primary controls and no seeding was carried out in these areas. In addition the rainfall analysis was carried out over an expanded area to ascertain possible spreading of the seeding results outside the defined target area. To facilitate future studies a Western Control area was defined and the Southern and Eastern areas were subdivided.

Clouds were regarded as suitable for seeding if their tops consisted of supercooled water drops at a temperature of  $-5^{\circ}\text{C}$ , could be defined as stratiform or mixed type, depth exceeded  $\frac{1}{3}$  terrain clearance, and if they were dense, durable, and compact and had a life-time exceeding 30 minutes.

The experiment was suspended and the rainfall figures omitted from the analysis, on days when aircraft or crew were unavailable; when the forecast wind at cloud heights exceeded 70 knots; or when there was excessive rainfall gradient between the north and south control areas.

The rainfall measurements in the target area were made by the Commission and those in other areas by the Bureau of Meteorology. All subjective decisions concerning the rainfall measurements were made by the Bureau of persons not knowing the seeding sequence. The Bureau also classified each day according to the meteorological situation, the categories being: frontal; cyclonic; N.W., N.E., S.E., S.W. stream weather; mixed.

#### *Operation*

Flying and seeding operations commenced in period 1 of Stage 2 of the cloud seeding experiment starting on 1 March 1971. The operation was continuous until the end of period 18 on 11 October 1971 when further seeding was suspended due to the storages reaching full supply levels. Flying operations ceased on 31 October 1971, and the Commission storages have been near spill limits since that time.

#### *Aircraft*

A De Havilland Canada Twin Otter aircraft with two crews was chartered from East West Airlines and operated at a high level of efficiency throughout the year.

#### *Cloud seeding staff*

The seeding operation was organized and conducted by C.S.I.R.O staff under the direction of Dr. E. J. Smith who also assisted with the appointment and training of two cloud seeding officers for the Commission.

#### *Cancelled days*

Eleven days were cancelled as follows:

April	2 days - 1 due to aircraft unserviceability 1 excess rainfall gradient
May	1 day - excess rainfall gradient
August	2 days - aircraft unserviceable
September	6 days - aircraft and crew in Canberra

This reflects the high standard of aircraft performance during the year.

#### *Flying and seeding*

The total flying time was 607 hours 55 minutes for cloud seeding operations with a total seeding time of 76 hours 23 minutes corresponding to about 11 hours per month during the seeding period. Despite the increased

number of seeding periods this was less than the average of 14 hours per month in 1970.

#### *Flight reports*

A report for each flight was prepared by the aircraft crew. These reports were prepared from log books, kept by each cloud seeding officer, in which all observations were entered during flight.

These included temperature soundings, position of aircraft while seeding, wind at cloud height, written description and sketches of clouds. Photographs of clouds were taken when possible during prolonged seeding operations. Synoptic charts, both surface and 700 mb. charts were supplied by the Bureau of Meteorology for sketches included in the flight reports.

#### *Cloud conditions*

During the 1971 operational season the total number of days was 245. Of these 11 were suspended and the remaining 234 are regarded as operational. Clouds were seeded on 55 days of which 2 were subsequently cancelled owing to rainfall gradient and there were 44 days in unseeded periods when clouds were observed to be suitable for seeding. Thus the total number of days with clouds suitable for seeding was 99—that is about 40 percent of the days in the period.

Comparison with previous years supports the earlier impression that in good years clouds suitable for seeding occur on about half the days, the fraction in a poor year being about one third.

#### *Results*

In cooperation with the Commonwealth Bureau of Meteorology the Commission processed the daily rainfall data from 140 rainfall stations throughout Tasmania. The details of the data processing are set out in the manual "ADP System for Cloud Seeding Experiment" by C. Denny, and every attempt has been made to maintain continuity with the data of the Stage 1 experiment.

The double ratios for autumn and winter combined for 1971 are shown in Table 1 compared with the corresponding double ratios for each of the previous seeded years. The autumn and winter results for 1971 are consistent with the previous years and the values of the double ratio using all data increased.

### **USE OF STREAMFLOW TO EVALUATE CLOUD SEEDING EXPERIMENTS**

Watson and Denny (1971) investigated the possible use of streamflow data from catchments in the seeded area and catchments outside the seeded area to evaluate the effect of the cloud seeding on the catchment yield.

They concluded:

(a) The use of the historical records of annual catchment yields from catchments in Tasmania is limited by the instability of the time series from the target catchments in relation to the control catchments.

(b) Evaluation will have to be based on the randomized period rainfall method during operational seeding with a consequent loss in the expected yield which may have resulted if continuous seeding were undertaken.

(c) The results of the analysis suggested an increase in the yield in the target area during the above average years when seeding took place which tended to support the results of the rainfall period analysis.

The relative position of the catchments studied is shown in Figure 2. The rank order series of the ratio of the Lake King William (T seeded area) and King at Crotty (C unseeded area) annual catchment yields are shown in Table 2. This illustrates that the ratio of T:C is not stable and that the ratio tends to increase with increasing relative wetness as measured by the ratio of the annual yield to the mean (C:MC). A positive shift is emphasized in the seeded years other than 1966 (Figure 3).

A multiple regression using the non-seeded annual yields from three catchments in the unseeded areas was derived and used to predict the expected annual yields from the Lake King William catchment during the seeded years. As shown in Figure 4, four out of the six seeded years show significant increases with an average increase of about 3½ percent.

If, by seeding continuously, a 25 percent increase in the Autumn plus Winter rainfall could be produced and a corresponding increase in the runoff from the Lake King

**Table 1. Yearly consistency of double ratios for Autumn and Winter combined.**

Year	Double Ratio Autumn Plus Winter		
	Target T/C	Target West TW/C	Target East TE/C
1964	1.36	1.36	1.40
1966	1.22	1.22	1.21
1968	1.28	1.40	1.12
1970	1.13	1.12	1.14
4 year Mean	1.19	1.25	1.13
1971	1.36	1.47	1.26
5 year Mean	1.23	1.28	1.18

Ref.: Smith et al., 1971

In this table the original control area is used, i.e.

$$\text{Control Area} = (\text{NC} + \text{SC})/2$$

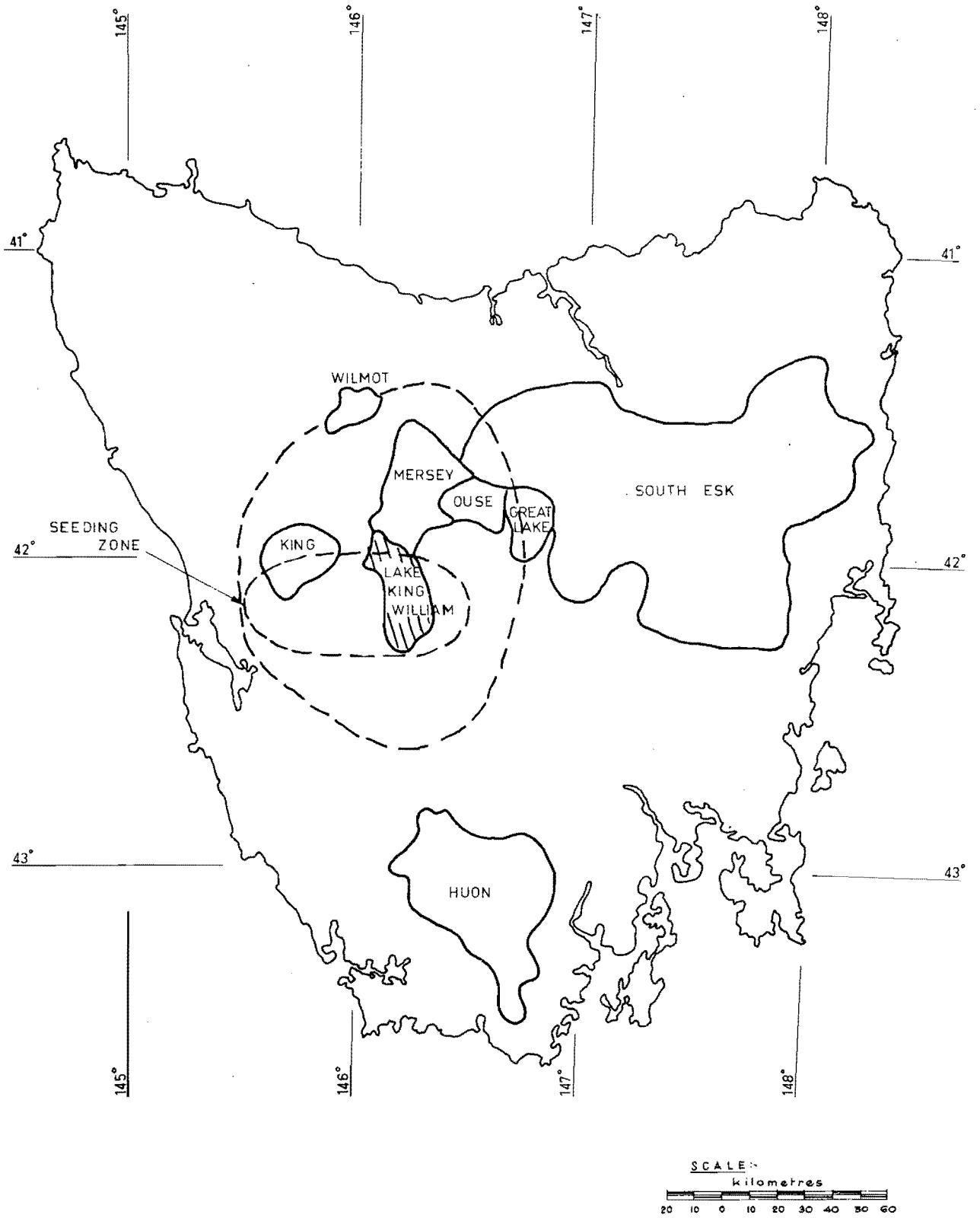


Figure 2. Target and control catchment areas.

William catchment, then this would be equivalent to about a 13 percent increase in the mean annual runoff. Seeding half the time as was done during the experiment could then result in an increase of about 6½ percent which is roughly comparable with the estimates based on the annual runoff analysis.

Another difficulty in using streamflow data for evaluation is the progressive development of the catchments for power generation. For example since the initial evaluation in 1971 two of the three control catchments have been either completely or partly regulated.

**CLOUD SEEDING AND WATER RESOURCES MANAGEMENT**

**Economic Evaluation**

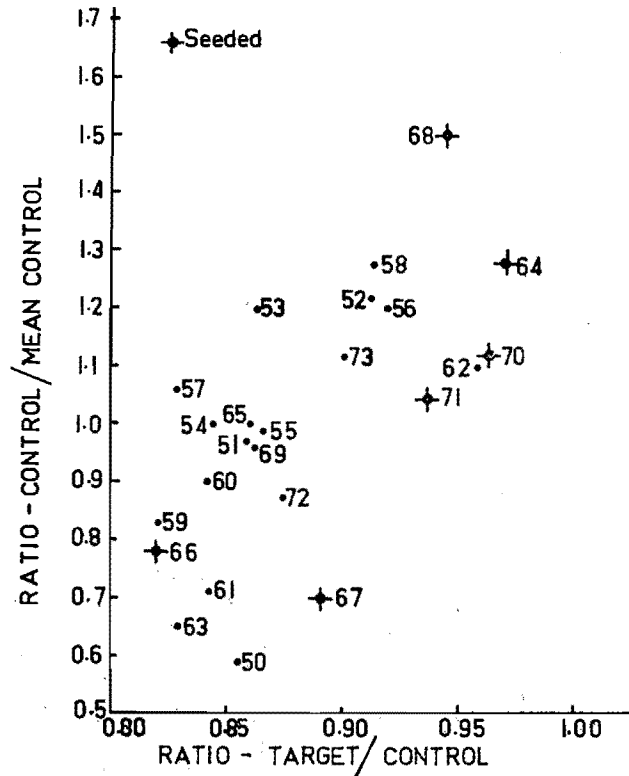
Cloud seeding introduces another variable into the already complex problem of water resources management. The following comments are primarily concerned with the power generating system in Tasmania.

The results, set out in the Cloud Seeding Experiments section, indicate rainfall increases which are dependent on special climatic conditions that predominate during a particular season. Although these conditions have a high degree of reliability in Tasmania it is likely that no

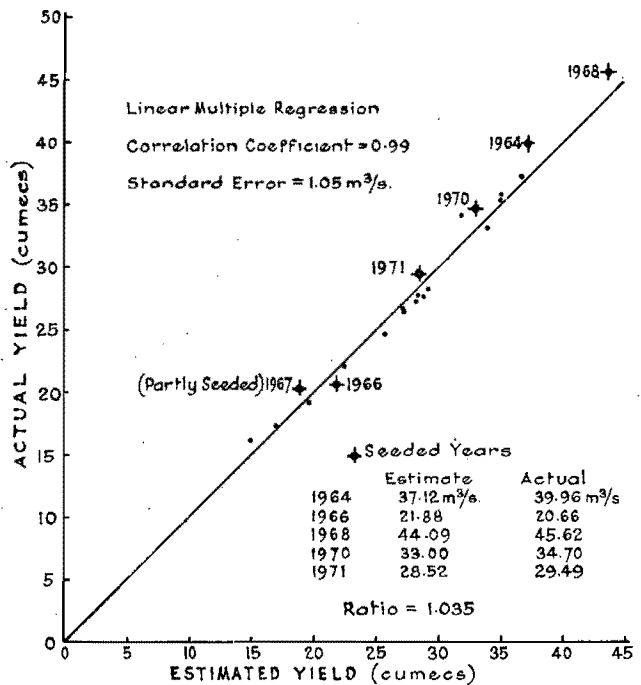
**Table 2. Rank order series ratio of Lake King William to King River.**

Rank	Year	Ratio T:C	Ratio C:MC
1	1964 (S)	0.971	1.28
2	1970 (S)	0.964	1.12
3	1962	0.959	1.10
4	1968 (S)	0.945	1.50
5	1971 (S)	0.938	1.04
6	1956	0.919	1.20
7	1952	0.914	1.22
8	1958	0.914	1.28
9	1973	0.904	1.11
10	1967 (PS)	0.891	0.70
11	1972	0.875	0.87
12	1955	0.866	0.99
13	1953	0.863	1.20
14	1969	0.863	0.96
15	1965	0.861	1.00
16	1951	0.859	0.97
17	1950	0.855	0.59
18	1954	0.845	1.00
19	1961	0.843	0.71
20	1960	0.842	0.90
21	1963	0.830	0.65
22	1957	0.829	1.06
23	1959	0.821	0.83
24	1966 (S)	0.820	0.78

S = seeded year  
 PS = partly seeded  
 T = Lake King William Yield  
 C = King River Yield  
 MC = Mean King River Yield



**Figure 3. Variation of ratio Lake King William yield to King River at Crotty yield with magnitude of yield.**



**Figure 4. Lake King William annual yields estimated from King River at Crotty, Wilmot River at Moina, Huon River at Frying Pan Creek.**

significant gains would occur during the dry years, thus increasing the variability of future inflows.

The increase in runoff into the Commission storages cannot be measured directly but as the increases seem to occur in association with moderate rain events at a time in the year when the catchments are generally saturated and losses are negligible it has been assumed that the increased rainfall will result in a corresponding increase in runoff.

From the results of daily system simulations in which small incremental increases in runoff to major storages were assumed, an estimate was made of the regulated yield which may be attributed to cloud seeding.

These results were used to estimate the economics of possible future cloud seeding based on the following assumptions:

(i) Cloud seeding would be carried out each year from April to September on a "controlled experiment" basis (i.e. seeding two periods in every three).

(ii) The increase in yield in the months April to September inclusive would be 12 percent in the Upper Derwent and Great Lake storages, 19 percent in the Lake Gordon catchments.

(iii) No gain in yield is credited to run-of-river catchments or minor storages.

(iv) The 1974 cost of a 6 month cloud seeding operation is \$180,000 per annum.

(v) The value of the energy due to cloud seeding is partly due to increases in system capacity and partly thermal fuel saving.

The simulation studies using forecasts of future load over a 10 year period showed that under median yield conditions cloud seeding would be a very economic proposition.

In actual practice the decision to cloud seed or not in any specific year is based on more detailed considerations such as:

- Present state of storages;
- Present load and short terms forecasts of load;
- Short term prediction of probable spill from major storages;
- Progress of construction program for additions to system;
- Present financial constraints;
- The need for experimental data, i.e. how much we are prepared to pay now for additional data, to enable greater certainty with decision-making.

This last factor is rather important when the results so far suggest that full time operational cloud seeding could

increase the mean annual flow by 10 percent, so seeding half the time means trading a 5 percent increase in yield for additional experimental data. A compromise is to seed for a greater proportion of the time but still retain some random control data for evaluation.

### Problems Arising

Obviously the above approach is rather unrefined and there are additional questions which may have to be faced:

(a) Can rainfall runoff models be developed in parallel with our knowledge of the rainfall modification process, so that the rainfall input to the model can be adjusted for seeding and subsequently used to forecast the possible increases in runoff? This would allow simulation of the cloud seeding operation in accordance with a defined set of rules.

(b) Can the predictions of seeding effects be accepted with sufficient confidence to base the design of future power generating and water supply systems on the increased yields?

(c) How far can results from one area be transposed to another?

(d) Can cloud seeding be treated as an on/off operation or are the optimum benefits achieved by mounting a continuous operation?

(e) If spill from storages is to be minimized what are the storage operation rules appropriate for determining when to seed or not?

(f) Will the intermittent nature of the present operations create staffing difficulties, including possible loss of expertise?

(g) What is the impact of seeding on the present assumptions made for the design of storage, spillway and diversion capacity? For example, increased variability in runoff may require increased storage and diversion capacities if full advantage is to be taken. Care would need to be taken to ensure the design floods are not exceeded.

(h) Although the evidence indicates that the environmental impact of cloud seeding is not significant what is the long term effect of increasing the average rainfall by 10 percent on the ecology?

### SUMMARY

Although operational cloud seeding by the State Government Authorities is virtually at a standstill an active research program is continuing in Australia to understand more fully the physical process of cloud formation and behavior. Parallel with the advances in cloud physics an applied research program is continuing

into the development of cloud seeding techniques aimed at increasing precipitation.

Cloud seeding has emerged as a feasible and economic proposition in Tasmania when the increases in precipitation can be utilized for power generation. However, it is still viewed as a marginal benefit and its inclusion in the power generating system presents a number of managerial, design and operational problems.

Comprehensive evaluation of the effect of cloud seeding requires relating the rainfall increases to runoff, a task which is approximate at best, hence improved hydrologic methods are needed if the impact of seeding is to be fully appreciated.

It is apparent that those who are concerned with watershed management now have to look beyond the catchment surface and include cloud seeding or weather modification within their sphere of interest.

#### ACKNOWLEDGMENT

The author acknowledges the permission of the Commissioner, Sir Allan Knight, C.M.G., M.E., B.Sc., B. Comm., F.I.E. Aust. to publish this paper. The opinions expressed in this paper are those of the author and not necessarily those of the Commission.

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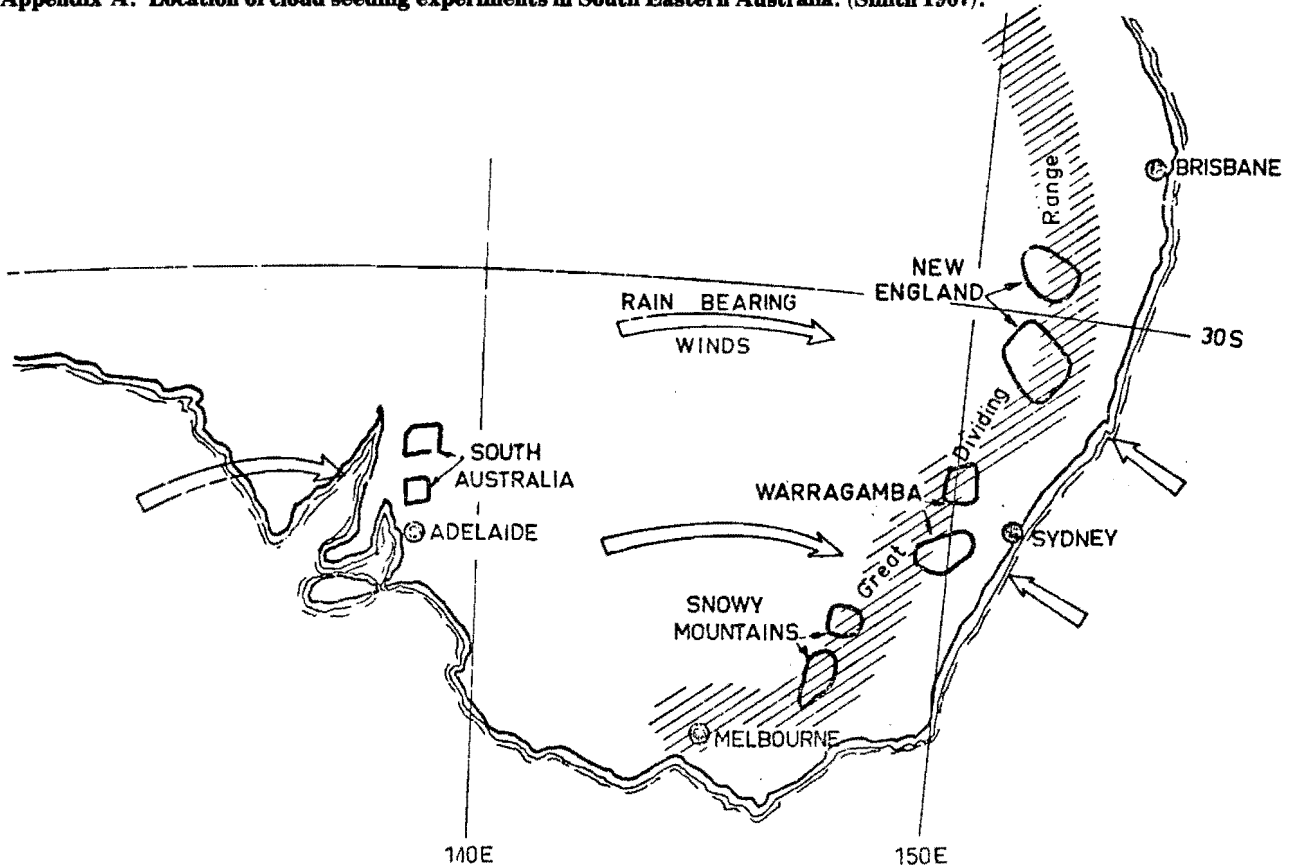
**Appendix A. Summary of area cloud seeding experiments in Australia.**

Experiment	Area	Period Length	Duration	Method	Result
1. Snowy Mountains	2600 km <sup>2</sup> El. 2000 m	12 days	1955-1959	Target and Control Areas fixed. Random 1 in 2 period seeding.	Mainly continental air mass. Initial result showed increase of 26% then decrease (a).
2. South Australia	2600 km <sup>2</sup> El. 800 m	12 days	1957-1959	Target Control Areas seeded random interchange.	Mainly maritime air mass Nil effect (b).
3. New England	8000 km <sup>2</sup> El. 800 m	12 days	1958-1963	Target Control Areas seeded random interchange.	Mainly continental air mass. Initial result showed increase of 30% then decreased (c).
4. Warragamba	2600 km <sup>2</sup> El. 800 m	1 day	1959-1963	Target Control Areas seeded random interchange.	Mixed continental, maritime air mass. Nil effect.
5. Darling Downs	7000 km <sup>2</sup> El. 800 m	12 days	1960-1961 Summers	Target Control Areas seeded random interchange.	Tropical air mass. Suspended after two years due to operational difficulties.
6. Tasmania	2500 km <sup>2</sup> El. 1000 m	12 days	1964-1970 Alternate years	Target and Control Areas fixed. Random 1 in 2 period seeding.	No effect spring and summer 15% to 20% increase autumn and winter statistically significant.

**Objective:** To seed deep, supercooled clouds over target area, cumulus clouds base seeded and stratiform at -5 C to -10 C level and establish whether rainfall increased.

**References:** (a) (Smith, Adderly, and Walsh, 1963)  
 (b) (Smith, Adderly, and Bethwaite, 1963)  
 (c) (Smith, Adderly, and Bethwaite, 1965)

**Appendix A. Location of cloud seeding experiments in South Eastern Australia. (Smith 1967).**



**Guide to cloud seeding experiment annual reports  
C.S.I.R.O. Division of Radiophysics**

Darling Downs	1960	R.P.R. 164
	1961	R.P.R. 165
South Australia	1957	R.P.R. 160
	1958	R.P.R. 161
	1959	R.P.R. 163
Snowy Mountains	1955	R.P.R. 150
	1956	R.P.R. 153
	1957	R.P.R. 154
	1958	R.P.R. 155
	1959	R.P.R. 157
New England	1958	R.P.L. 161
	1959	R.P.L. 163
	1960	R.P.R. 145
	1961	R.P.R. 146
	1962	R.P.R. 147
Warragamba	1963	R.P.R. 156
	1959 - 1960	R.P.L. 156
	1961	R.P.L. 160
	1962	R.P.R. 144
Tasmania	1963	R.P.R. 152
	1964	R.P.R. 166
	1965 - 1966	R.P.R. 168
	1967 - 1968	R.P.R. 169
	1969 - 1970	R.P.R. 174

**Appendix B. Summary of state government cloud seeding operations.**

South Australia	17. 4.68 - 7.10.68	Dept. of Agriculture South Eastern S.A.
A.C.T.	10. 3.68 - 10. 5.68	Department of Interior (Commonwealth)
Western Australia	24. 4.67 - 31.10.67	Public Works Dept.
	1. 4.68 - 31.12.68	Perth
	28.11.67 - 29. 2.68	P.W.D.
Queensland	2. 1.69 - 31. 3.69	Meekatharra
	5. 4.65 - 31. 5.65	Dept. of Primary Industries
	20. 2.67 - 7. 3.67	
	15. 9.69 - 14.12.69	
	24. 4.65 - 13. 5.65	Mount Morgan
Victoria	15. 4.66 - 13. 5.66	
	27. 1.66 - 24. 2.66	Forestry Dept.
	15. 1.67 - 1. 3.67	
	9. 8.66 - 7.11.66	Dept. of Agriculture
	3. 5.67 - 25.10.67	Western Victoria
	4. 1.68 - 30.11.68	
	1. 5.69 - 31.10.69	
New South Wales	30. 4.70 - Dec. 1970	
	4.11.67 - 31. 3.69	Dept. of Agriculture
	1.12.69 - 31. 3.70	Central Catchment Areas and Forests
	8. 5.65 - date	Dept. of Agriculture, Cobar
Tasmania	5. 5.66 - 31.12.66	Dept. of Agriculture, Tamworth
	1. 1.67 - 30. 9.69	Dept. of Agriculture, Wagga
	1. 3.71 - 11.10.71	Hydro-Electric Commission
	1.10.73 - 30.11.73	H.E.C. for Dept. of Agriculture

# Water Use on Rangelands

Farrel A. Branson\*

Recent and shocking disclosures of the limited capacity of world agriculture to supply adequate food for our burgeoning human population adds another dimension of importance to this and similar conferences. Since water is essential for life (both food and nonfood organisms) on this planet and also in short supply in many areas, we need to increase our knowledge of its supply and use.

The seemingly all-inclusive title was selected because of the wide range of topics covered in this paper. Topics discussed on the following pages include: (1) general relationships between vegetation, runoff, and precipitation, (2) soil-vegetation-water relationships, (3) water harvesting on rangelands, (4) range water spreading, and (5) water management on rangelands.

## VEGETATION AS RELATED TO RUNOFF

Of the approximately 40 percent of the world's land surface that is classified as rangeland, over 80 percent is within the arid and semi-arid zones. By definition, this means that runoff per unit of area is low but when we consider the water resource represented by precipitation on these lands the quantity is enormous. Runoff as a product of these lands has often been overemphasized and the much larger component, evapotranspiration, underemphasized. On rangelands, evapotranspiration is often more than 95 percent (Figure 1) of precipitation. Obviously, much more management effort should be devoted to this component of the water resource. As shown in this graph, estimated runoff is 4 percent and groundwater recharge less than 1 percent. Groundwater recharge seems to be a very small component and remains difficult to measure or estimate.

This graph is generalized and intended only to fit many typical situations. For a large watershed (150 km<sup>2</sup>) in Arizona with predominantly gravelly soils, Renard (1970) estimated groundwater recharge to be about 7 percent of annual precipitation.

The source of the runoff estimates is the graph by Langbein and Schumm (1958) (Figure 2) showing the

relationships between annual precipitation and annual runoff. Runoff increases exponentially as precipitation increases; stated differently, runoff as a percent of precipitation becomes greater as precipitation increases. This has some significance when management practices or treatments that may increase runoff are considered.

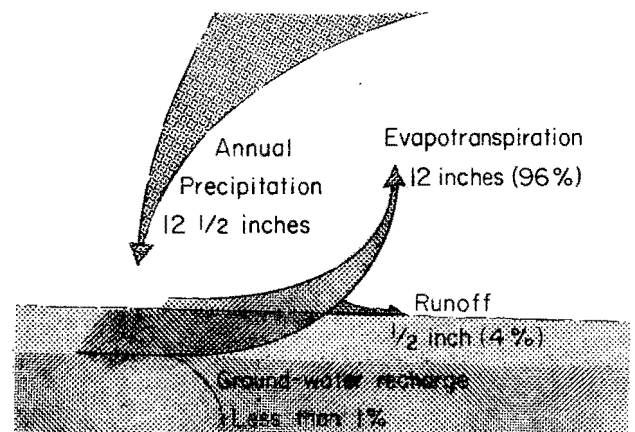


Figure 1. Diagrammatic disposition of 12½ inches (318 mm) precipitation as evapotranspiration, runoff, and groundwater recharge.

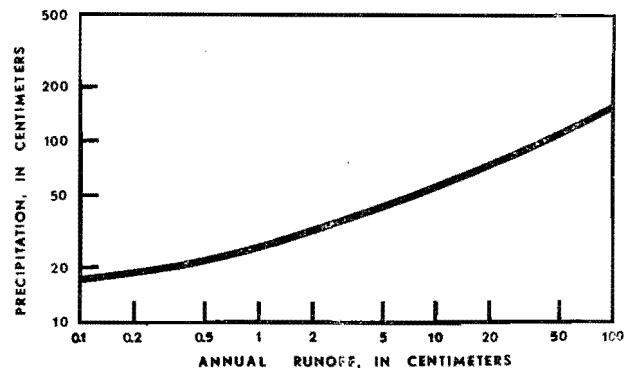


Figure 2. Relation between annual precipitation and runoff data have been adjusted to that expected for a climate with 10°C mean annual temperature. (Adapted from Langbein and Schumm, 1958).

\*Botanist, U.S. Geological Survey, Box 25046, Denver Federal Center, Denver, Colorado.

Runoff as percent of precipitation for different vegetation zones of the Rio Grande Basin is shown in Figure 3. These data indicate that 10 inches (25 cm) or more precipitation must occur before there is a significant amount of runoff. It is undoubtedly incorrect to think of these data as runoff from different vegetation types. Rather they are runoff quantities from environmental complexes with major variables including vegetation, soil, temperature, altitude, and precipitation zones. The complexity does not alter the fact that meaningful relationships exist that can be used for prediction purposes as is indicated by the highly significant correlation coefficient of 0.95 for precipitation and percent runoff. However, one would expect regression lines to differ somewhat with major shifts in latitude.

The effects of shifts in latitude and attendant temperature effects on runoff as percent of precipitation are indicated in Figure 4. According to these data, Douglas fir-Aspen in Colorado have about 27 percent runoff from 22 inches (56 cm) precipitation whereas white and Douglas fir in Arizona with 32 inches (81 cm) have only 9 percent runoff. In agreement with the data in Figure 3, this 9 percent runoff differs greatly from results in Oregon (Rothacher, 1970) where runoff is 63 percent of the 90 inches (225 cm) precipitation. Evapotranspiration, the remainder of the water balance equation (precipitation = runoff + evapotranspiration) becomes a smaller percentage as annual precipitation increases.

The curve shown in Figure 2 should be a wide band instead of a line if it were to include variations in runoff that one finds within precipitation zones. Within a single macroclimate, large variations in runoff may occur because of differences in lithology, vegetation cover, watershed orientation, and other factors. For example, in the Badger

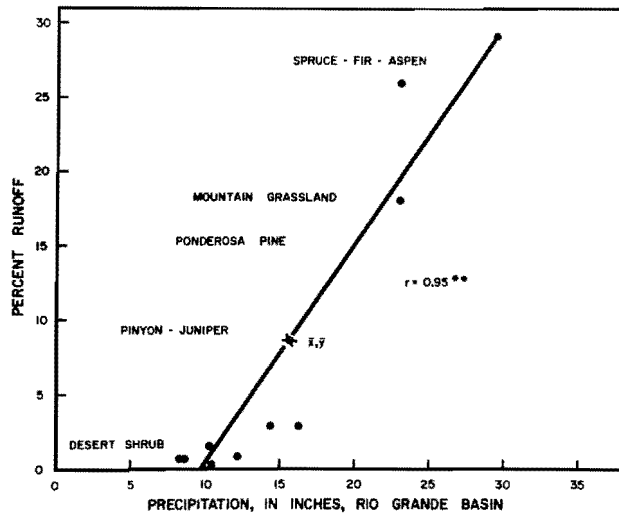


Figure 3. Runoff as percent of precipitation for different vegetation and precipitation zones of the Rio Grande Basin of Colorado and New Mexico (computed from data by Dortignac, 1956). \*\* = significant at the 1% level.

Wash Basin in western Colorado (Figure 5) with the same annual precipitation (8.5 in., 216 mm) reaching all of the 17 watersheds, some have runoff five times as great as others. These differences are caused by different geologic terrains which range from sandy in some to clayey in others. The relationship between bare soil (this excludes live vegetation, standing and detached mulch, and rock particles larger than 2 mm) and runoff is highly significant (Branson and Owen, 1970). Similar results were found in predominantly grass-covered watersheds (11 in., 279 mm annual precipitation) in north central New Mexico (Shown, 1971) but here vegetation plus mulch gave a higher correlation coefficient ( $r = 0.89^{**}$ ) with runoff than did bare ground. These differences are attributed to kinds of soil material prevalent in the two sets of watersheds (shale particles at Badger Wash in Colorado versus resistant sandstone

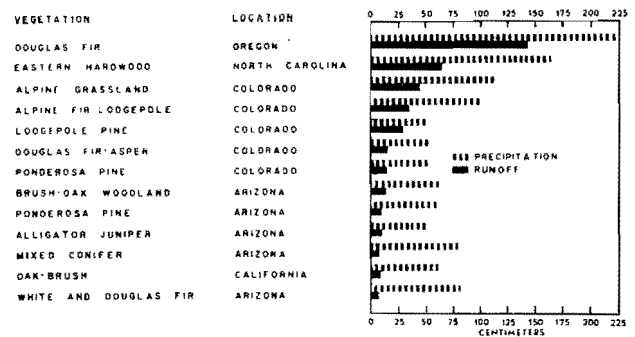


Figure 4. Precipitation and runoff for different types. (Data adapted from Rothacher, 1970; Hoover, 1944; Lewis, 1966; Coleman, 1953; Brown, 1970; Rich, 1961.)

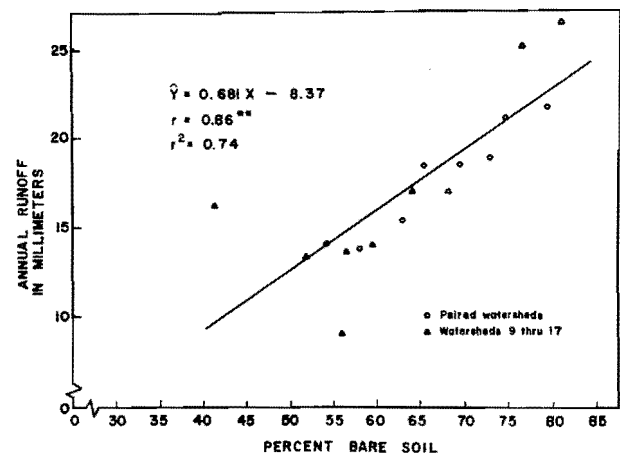


Figure 5. Regression line for percent bare soil versus 15-year average annual runoff for 17 watersheds (after Branson and Owen, 1970). Four of the "paired watersheds" were protected from grazing during the 15 years of study (Y = estimated "y" value that can be computed from the equation shown when X values are known,  $r$  = correlation coefficient, and  $r^2$  = coefficient of determination or amount of variability in percent accounted for by the data).

particles in New (Mexico). Kincaid and Williams (1966) in Arizona also found highly significant inverse relationships between crown cover and runoff.

There are many methods of estimating runoff from ungaged watersheds that do not include vegetation measurements. It would not be suitable for discussion under the topic heading of this section but for proper perspective a brief listing would be desirable. They include: (1) geomorphic measurements such as angle of junction, drainage density, mean slope, watershed area, relief ratio, and circularity (see Branson et al., 1972 for a brief discussion); (2) watershed modeling which may or may not have the input of vegetation measurements; (3) channel geometry measurements; and (4) extrapolation from established gaging stations.

Vegetation modification effects are included under a topic discussed above but some discussion of them is appropriate here. Clearing of woody vegetation for the vegetation types shown in Figure 4 has resulted in varying effects on total annual runoff (Figure 6). As expected the runoff is larger from high precipitation zones but the percentage increases in low precipitation zones are sometimes surprising. For example, in chaparral of high density, Brown (1970) shows runoff was only 2.5 cm before treatment, but after treatment it was nearly 15 cm per year, an increase of nearly 600 percent. However, conversion of a watershed having low chaparral density did not cause an increase in runoff.

**VEGETATION AND SOIL-WATER RELATIONSHIPS**

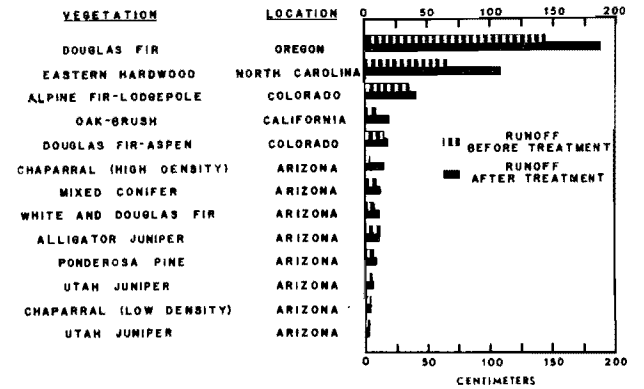
In this section a complete treatise on plant-water relationships will not be attempted but the purpose will be to consider some of the new information as it applies to rangelands. Excellent reviews of the subject are found in books by Kramer (1949), Kozlowski (1964, 1968), and Slatyer (1967).

Of particular interest are the energy relationships in the soil-plant-air thermodynamic continuum. These are shown diagrammatically in Figure 7. The curve shown would change somewhat with changing soil-moisture conditions and for different macrohabitats. The general magnitudes of the force gradients in soil, plant, and atmosphere are shown. Obvious the moisture-extraction force exerted by the plant must exceed moisture-retention force of the soil, and it can be seen from the curve that moisture-extraction force of the atmosphere greatly exceeds that of plant or soil.

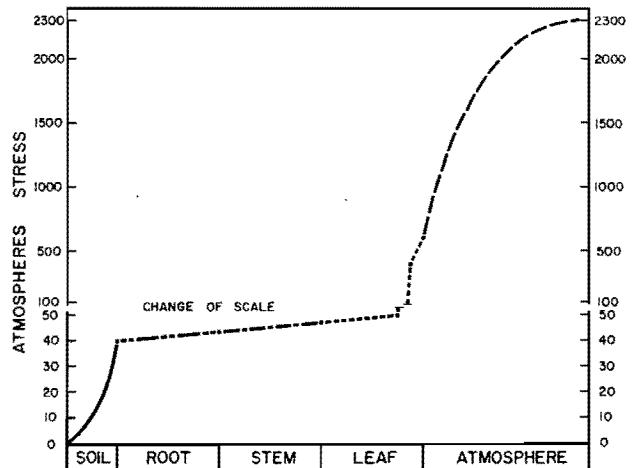
Each segment of the curve needs some interpretation. Soil-moisture stress would not normally be zero except where a water table was in reach of plant roots and for upland sites the curves would be quite different for maximum wet and maximum dry conditions during a growing season. The increase in stress from root to leaf has

two components: (1) resistance to flow within the plant and (2) the effect of gravity. Since 1 bar or 1 atmosphere is equivalent to a water column of about 10 meters, gravitational force is a minor component of change in force shown within the plant. A sharp increase in the force gradient occurs in the mesophyll cells adjacent to substomatal cavities and within substomatal cavities. The gradient is also steep from the leaf surface to the free atmosphere.

Two relatively recent developments make it possible to study the energy relationships of the soil-plant-atmosphere continuum under field conditions. The calibrated filter-paper developed by McQueen and Miller (1968) permits measurement of soil-moisture stresses of from near 0 to 1,500 bars in field samples. Also, the pressure chamber method of determining internal-moisture stress in plants (Scholander et al., 1965) gives



**Figure 6. Runoff before and after vegetation conversions, clearing, or replacement with herbaceous vegetation, for different vegetation types. (Data adapted from Rothacher, 1970; Hoover, 1944; Lewis, 1966; Coleman, 1953; Brown, 1970; Rich, 1961.)**



**Figure 7. Energy profile of the soil-plant-water continuum. (Modified from Kozlowski, 1964.)**

rapid and accurate field measurements of moisture extraction forces exerted by plants.

A diagram showing the principles involved in the use of the pressure chamber is shown in Figure 8. When a twig is cut from a woody plant, water retreats in two directions from the cut surface. If the twig is then placed in a chamber and enough force applied to move water back to the

cut surface, that force as read from a pressure gage is a measure of the force being exerted by the plant to remove moisture from the soil.

The calibration curve for filter paper is shown in Figure 9. We use a tubular auger 5 cm in diameter for soil sampling. All the soil from each 10 cm depth is placed in a "zip lock" plastic bag and a filter paper, previously treated

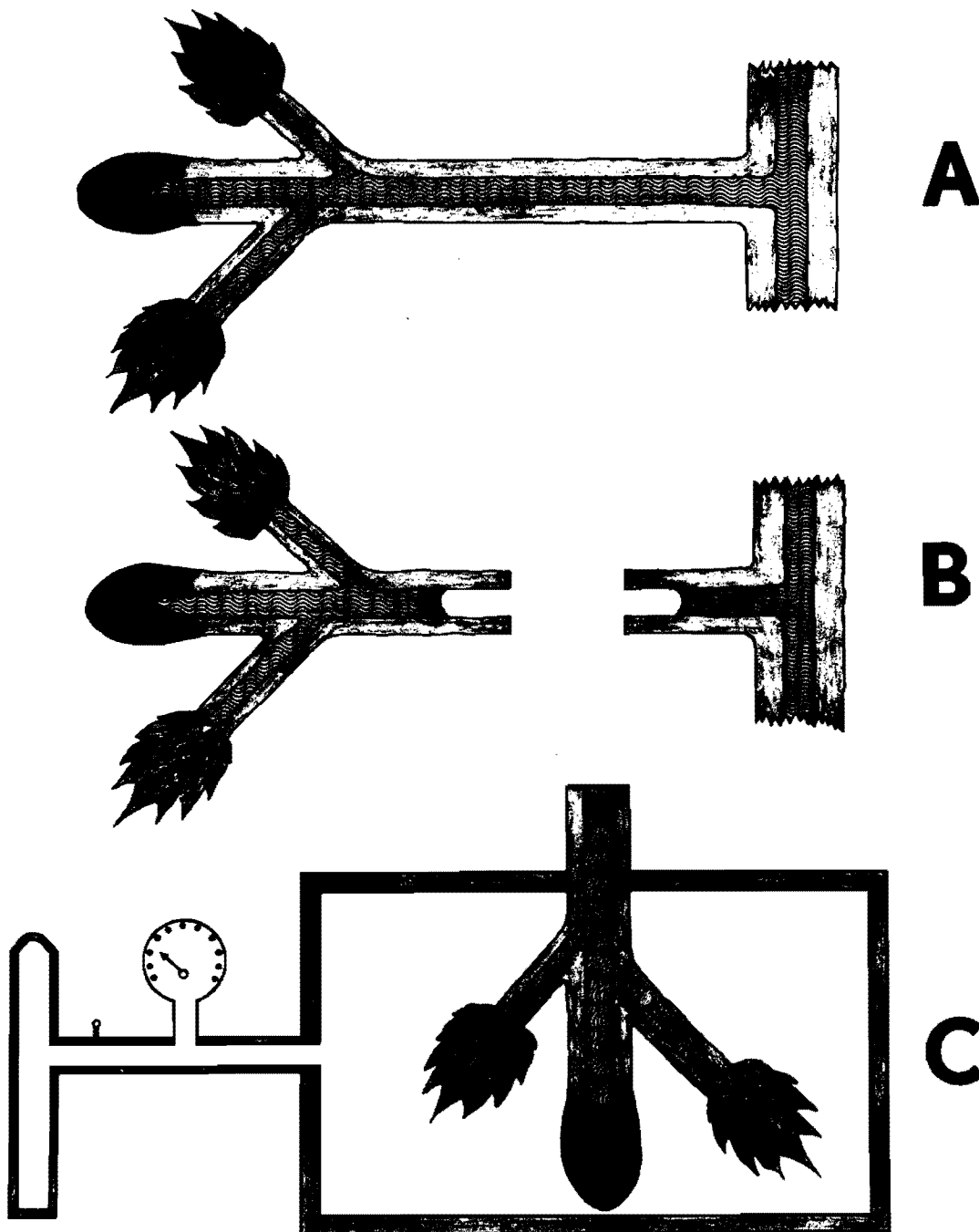


Figure 8. Diagram showing an uncut twig (A), a cut twig showing retreat of water, the light-colored portion, from the cut surface (B) and the twig inserted in a pressure chamber (C) and enough pressure applied to force internal water back to the cut surface.

to prevent decomposition, is inserted with each sample. Each bag is then placed in a metal container and the lid sealed with plastic tape. The samples are stored at about 20°C for a week or more to achieve moisture equilibrium between paper and soil. Moisture contents of paper and soil are determined by weighing before and after oven-drying. The force with which moisture was retained by the soil at the time of sampling is then determined from the moisture content of the filter papers and use of the calibration curve shown in Figure 9. This force can then be compared with internal-plant stress measured at the time of soil-moisture sampling.

Moisture contents are computed as grams per gram of dry material. The moisture depth in the soil profile is then computed as grams of water per gram of soil, and this times the grams of soil present per cubic centimeter times the depth of the profile gives depth of water stored at the sampling time.

Moisture retention curves differ for each profile. These curves can be approximated for the entire range from saturation to dryness using the empirical method developed by McQueen and Miller (1974). The generalized model they presented is shown in Figure 10. To prepare a model for a particular soil they suggest the following procedure:

1. Plot available data for soil water and pF in the range from 2.35 to 5.0 (pF is the common logarithm of the height in centimeters of a column of water capable of producing a pressure equivalent to the force with which moisture is retained by soils).
2. Draw a straight line from pF 6.25 on the ordinate through the centroid of the data points to pF of 0 on the abscissa.
3. The capillary segment is unstable. To approximate it, draw a line through the capillary limit on the zero-moisture-content axis (0, 2.9) and the point where the adsorbed segment intersects the pF = 2.35 level on the adsorbed moisture line (water = 2.35). Draw a vertical line up from the moisture content of the soil at saturation (W, 0.0). Sketch a curved line from (M, 2.35) to (M, 0.0) as shown in Figure 10.

Examples of moisture retention models for soils ranging from gravelly to clayey are shown in Figure 11.

An example of maximum wet and maximum dry soil stress curves measured during a growing season is shown in Figure 12. Many similar graphs for plant communities in the western United States could be shown but this one as an example should suffice. It is important to note that the two curves come together at depth. The similarity of the curves at depth indicates an annual pattern of water

storage and evapotranspiration with limited possibility of water moving to the water table. The "community stress limit" shown is nearly 100 bars which is near the maximum internal-plant stress we have measured elsewhere for this species. The maximum soil-moisture stress of about 700 bars for 0-5 cm depth far exceeds the capacity of the plant to remove water and is attributed to solar energy reaching the soil surface. Solar energy is considered the cause for evaporated water, E in Figure 12.

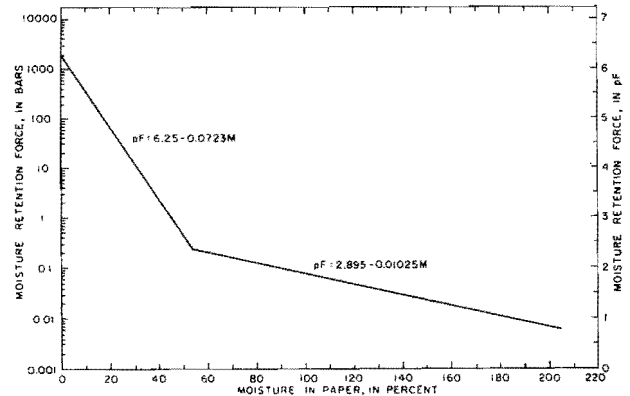


Figure 9. Calibration curves for filter paper (Schleicher and Schnell No. 599 white ribbon) moisture and soil-moisture retention forces (adapted from McQueen and Miller, 1968).

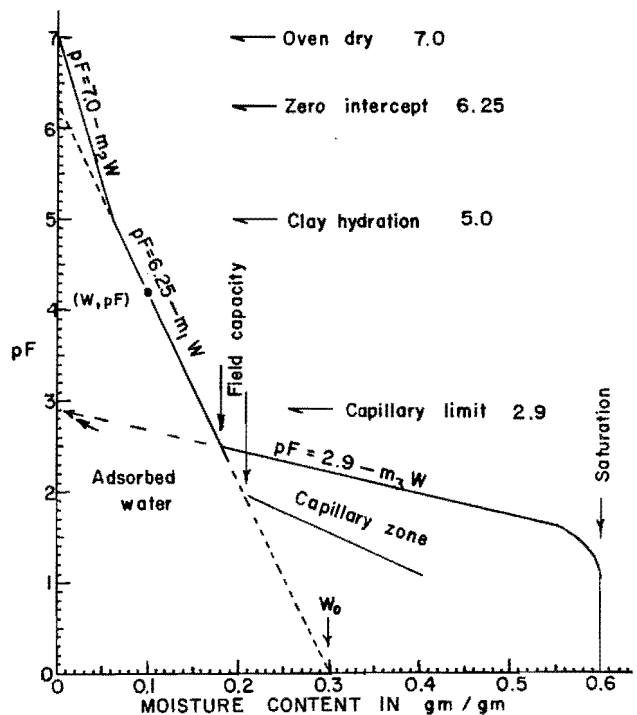


Figure 10. Model for method of approximating soil-moisture characteristics from limited data (from McQueen and Miller, 1974).

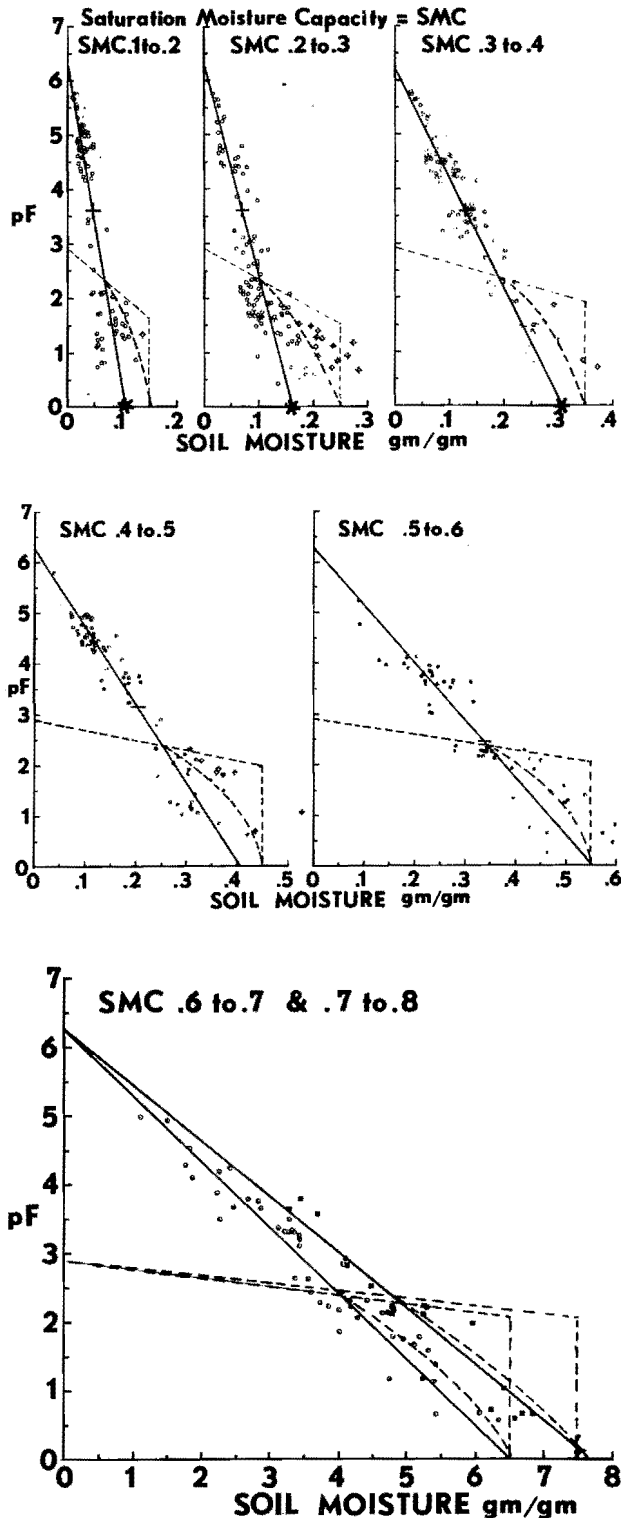


Figure 11. Moisture retention models for soils ranging from gravelly (saturation moisture capacity of 0.1 to 0.2 or 10% to 20%) to clayey (SMC of 0.7 to 0.8). (From R. F. Miller, written commun. 1975.)

We have explored the relationships of internal-plant stress to a number of environmental variables (Figure 13) and have found plant stress to be most closely related to the minimum soil-moisture stress that may occur at any depth in the soil profile (Branson and Shown, 1975). Results shown in Figure 13 are for a big sagebrush community in north central Colorado. These results are in agreement with those of Gardner (1965) who found that roots of birdsfoot trefoil (*Lotus corniculatus* var *tenuifolius*) had considerably less resistance to water movement than the surrounding mineral soil thus permitting water to move in roots across zones high resistance from the zone of lowest soil moisture stress. Or stated differently, water flow through the plant is easier than water flow through the soil.

Soil-moisture stress in the B and C, B<sub>3</sub> C<sub>1</sub>, and B<sub>2</sub> horizons were also closely related to internal-plant stress. These results indicate that relatively inexpensive and rapid plant stress measurements might be used to estimate soil-moisture stress. Of even more practical significance is the highly significant negative correlation of plant stress with soil-moisture storage. If plant stress measurements

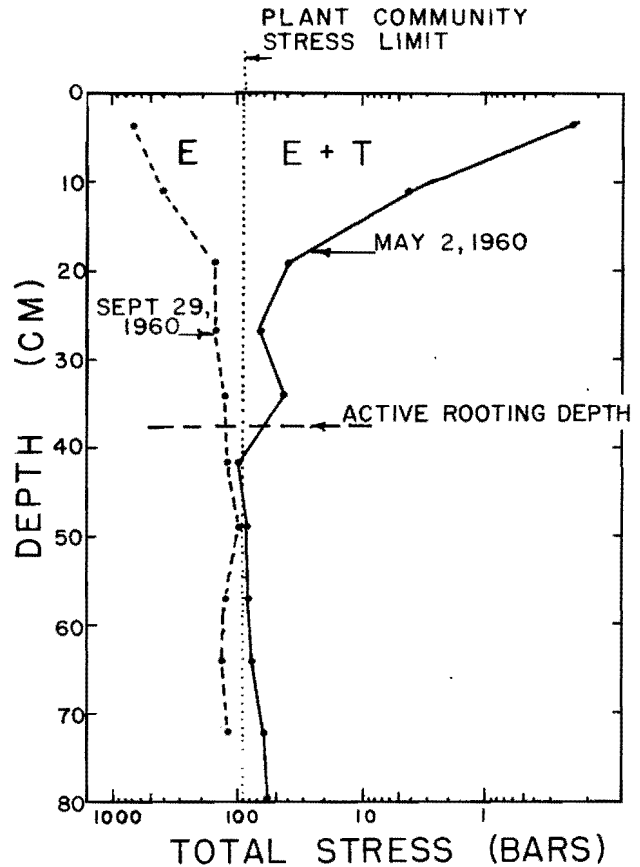


Figure 12. Soil-moisture stress profiles for wet (May 2) and dry (Sept. 22) seasons in a nuttall saltbush (*Atriplex nuttallii*) community in Montana. E indicates evaporation and E + T indicates evaporation plus transpiration (from Branson, et al., 1970).



can give reliable estimates of soil-moisture storage, economical estimates of evapotranspiration quantities, potential forage yields, and possibly optimum times for herbicide applications may be estimated.

Hour of day, net radiation, and wind velocity were significantly related to inter-plant stress but vapor pressure deficit, air temperature, soil temperature, A-horizon soil-moisture stress, and atmospheric-moisture stress were not. These results for atmospheric stress differ greatly from those reported for irrigated crops (van Bavel et al., 1963) and plants grown in moist soils (Haas and Dodd, 1972; Easter and Sosebee, 1975). Van Bavel et al., state: "We conclude that a full stand of sudan grass under conditions of high temperature (Tempe, Arizona), high light intensity, very low humidity of air, and sufficient soil moisture—in short a highly evaporative environment—can transpire on atmospheric demand." Under conditions present at our study site (Branson and Shown, 1975) soil-moisture stress exerted the most influence on internal plant stress and atmospheric demand was of no significance. It is probable also that plant characteristics that inhibit desiccation such as stomatal closure, light-colored leaves, and trichomes on the leaf surfaces exert some influence on water loss from big sagebrush (*Artemisia tridentata*) and numerous other range plants.

The probable general relationships between plant effects (stomatal resistance), atmospheric demand, soil-moisture stress, and transpiration are illustrated in Figure 14. The point at which plant effects become more important than atmospheric demand is unknown but for plants growing in arid and semiarid environments plant effects must become dominant early in the growing season as soil-moisture stress rapidly increases. Increases in soil-moisture stress or resistance to water movement in soils plus increases in stomatal resistance results in rapid decreases in evapotranspiration. These conditions contrast sharply with the irrigated crop environment described by

van Bavel et al. (1963) where soil-moisture stress was maintained at a very low level.

Minimum soil-moisture stress, the variable most closely related to internal-plant stress, occurs at various depths in the soil profile during the growing season (Figure 15). Not only does the depth vary, the actual minimum stress measured is variable throughout the growing season. For example, the lowest minimum soil-moisture stress measured was 0.2 bar in April in the A-horizon; in July the lowest soil-moisture stress measured was 10.5 bars in the upper portion of the C horizon.

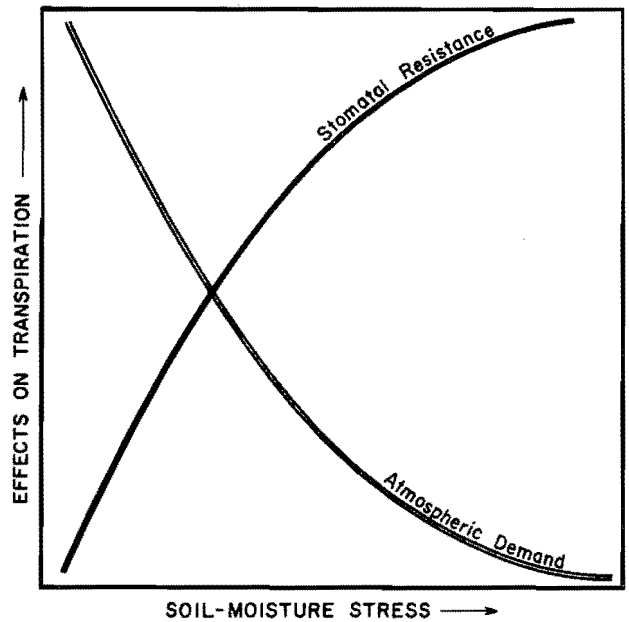


Figure 14. Diagram showing probable interrelationships of soil-moisture stress, atmospheric demand, and plant effects (stomatal resistance, morphologic features, etc) as they affect transpiration.

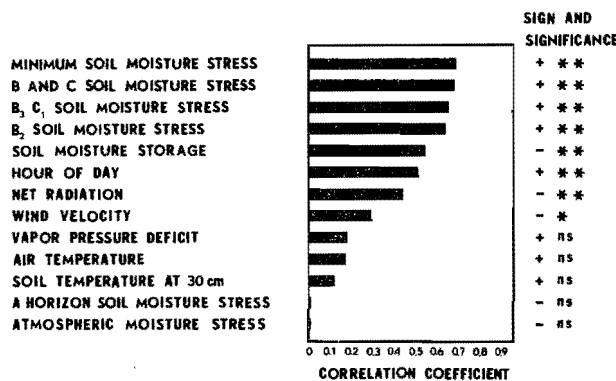


Figure 13. Correlation coefficients for internal plant stress as related to soil-moisture stress and additional environmental variables (from Branson and Shown, 1975). \*\* = significant at the 1% level, \* = significant at 5%, and NS = not significant at the 5% level.

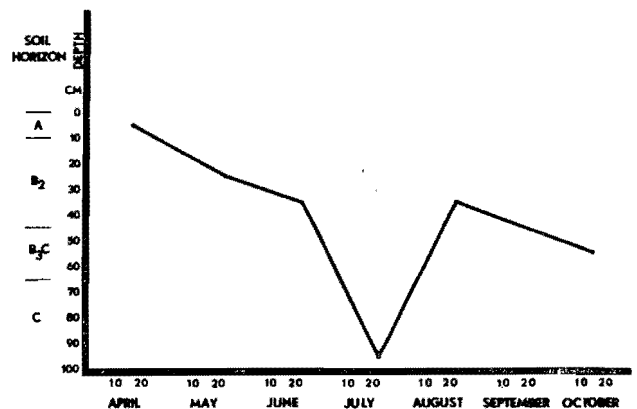


Figure 15. Depths in the soil profiles at which minimum soil-moisture stress occurred on the dates measurements were made (from Branson and Shown, 1975).

Maximum, minimum, and mean internal plant-moisture stresses for 10 shrub species are shown in Figure 16. As appears true for salinity tolerance (Daubenmire, 1948), maximal stresses attained by species seems a more reliable index of drought tolerance than mean or minimal values. Maximum plant-stress values shown range from 103 bars for nuttall saltbush (*Atriplex nuttallii*) to only 40 bars for rubber rabbitbrush (*Chrysothamnus nauseosus*). Nuttall saltbush occupied a dry upland site and rubber rabbitbrush occupied small floodplains at least intermittently supplied with groundwater.

Seasonal patterns of internal plant stress, minimum soil-moisture stress, and daily precipitation are shown in Figure 17. From late May through September both plant and soil stresses increase followed by a decline in both stresses as quantity and frequency of precipitation increase in the fall.

Each data point for plant stress in Figure 18 is the average of 10 measurements (5 measurements at each of two sampling sites). The average is 103 bars but one of the values was 117 bars, a value slightly higher than the 112 bars reported as the maximum stress measured for *Acacia aneura* in Australia (Slatyer, 1961). This value (117 bars) is nearly eight times the 15 bars soil-sorption force often considered to be the "wilting point."

Correlation coefficients for the relationship between internal-plant stress and minimum soil-moisture stress for 11 shrub communities near Grand Junction, Colorado, are shown in Figure 18. The highly significant coefficients account for as much as 86 percent of the variability and indicate that, by means of regression lines, internal-plant stress for most of these species could be used to estimate minimum soil-moisture stress. The correlation coefficient is low for the moist and salty mat saltbush (*Atriplex corrugata*) site, nonsignificant for the rubber rabbitbrush site which receives run-in moisture, and meaningless for the greasewood (*Sarcobatus vermiculatus*) site which has a constant supply of groundwater or zero minimum soil-moisture stress at 3.7 m.

Additional evidence showing the close relationship between internal plant stress and quantity of moisture

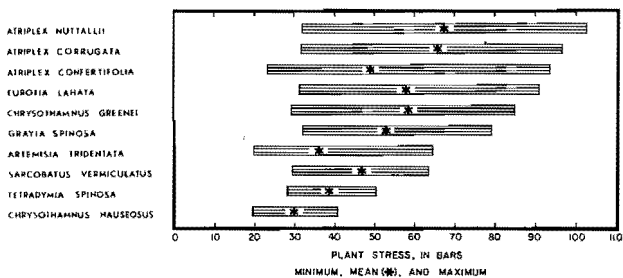


Figure 16. Minimum, mean, and maximum internal-plant stresses for 10 shrub species (from Branson, et al., in press).

stored in the soil at the time of plant stress measurement is shown in Figure 19. These data are the result of a more intensive study than that shown previously (Figure 13). More data sets and more species are included. In general, the coefficients are slightly lower than for the relationship between plant stress and minimum soil-moisture stress but many are highly significant. A similar relationship between soil-water content and internal plant stress has been reported for red pine (*Pinus resinosa*) in Minnesota (Sucoff, 1972). As was true for plant and soil-moisture

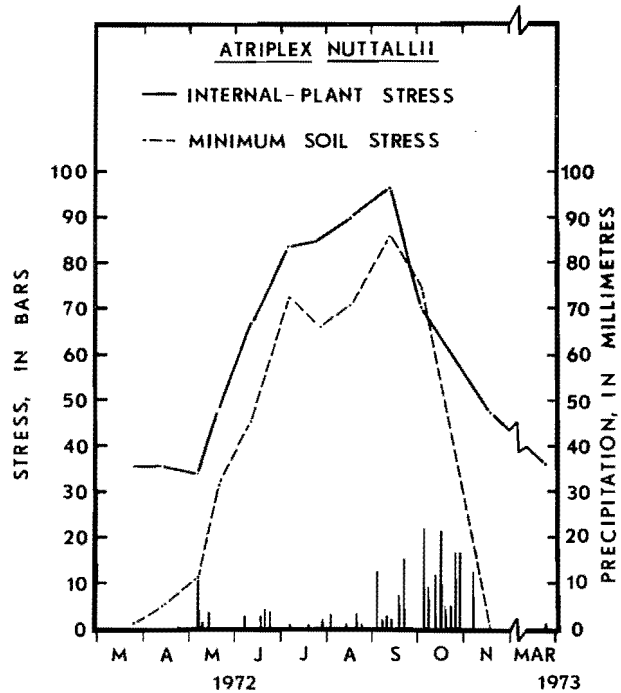


Figure 17. Seasonal patterns of internal-plant stress, minimum soil-moisture stress and precipitation (vertical bars) for two nuttall saltbush sites (from Branson, et al., in press).

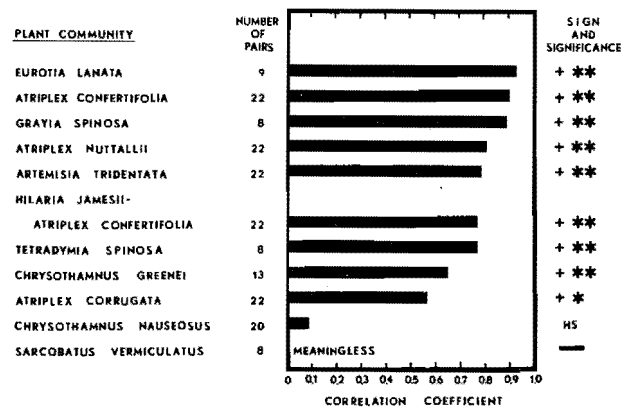


Figure 18. Linear correlation coefficients for the relationship between internal-plant stress and minimum soil-moisture stress measured in 11 plant communities (from Branson, et al., in press).

stress, the relationship between plant stress and soil-water storage is best for upland communities and poorest for moist lowland sites. The highly significant correlation coefficients shown in Figures 13, 18, and 19 indicate that regression lines could be used to estimate any of the three variables (soil water stored, minimum soil-moisture stress, and internal-plant stress). Of the three, internal-plant stress is most easily and rapidly measured and could be used to estimate either of the other two variables desired.

**Evapotranspiration**

This topic has been discussed by others in this workshop, thus only one of the several types of water-budget methods will be treated. Changes in soil-moisture storage has been used by several investigators (Brown and Thompson, 1965; Tew, 1967, 1969; Johnson et al., 1969; Johnston, 1970; and Tabler, 1968) to determine evapotranspiration quantities by periodic soil-moisture measurements. Several equations that can be used to estimate evapotranspiration from soil-moisture measurements are shown in Figure 20.

Equation 1 can be used if there are no significant precipitation events during the period of measurement. This equation can be used where moisture recharge occurs during the non-growing season. If significant soil-moisture recharge events occur during the growing season, amounts determined by before and after measurements should be added. If a water table is within reach of plant roots, the water represented by water-table fluctuations should be added to amounts of water determined by either Equation 1 or 2. If precipitation is known, runoff can be estimated by subtracting evapotranspiration from precipitation. If evapotranspiration exceeds precipitation, as frequently occurs on lowland sites with long durations of overland flow, the amount of run-in moisture can be accessed by subtracting precipitation from evapotranspiration. An example of data obtained by using Equation 2 for 14 plant communities in northeastern Montana is shown in Figure 21. The horizontal bars represent evapotranspiration and by comparing them with annual precipitation, runoff or run-in water may be estimated. Four of the plant communities evapotranspired more water than the annual precipitation (run-in sites) and 10 less (runoff sites). In contrast to almost twice the annual precipitation being evapotranspired by the western wheatgrass community, runoff from the nuttall saltbush slick was over 80 percent of the annual precipitation. Relationships such as those shown in Figure 21 can be used to estimate runoff from watersheds. Extrapolating these data to a nearby, small (6 mi<sup>2</sup>, 15.5 km<sup>2</sup>) watershed having known community coverage (Figure 22) and known runoff, the algebraic sum of community coverage and runoff or run-in for each community gave an estimated runoff of 12.4 percent of the annual precipitation. This was an underestimate of the measured (8-year average) 15.5 percent runoff but an overestimate for the entire Willow Creek basin which has a

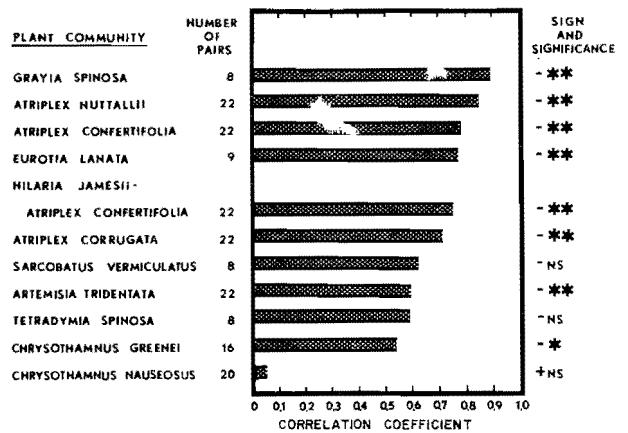


Figure 19. Curvilinear correlation coefficients (Y = be<sup>mX</sup>) for the relationship between soil-water storage and internal-plant stress in 11 plant communities (from Branson, et al., in press).

1.  $ET = MAX_{SMS} - MIN_{SMS}$
2.  $ET = MAX_{SMS} - MIN_{SMS} + \Delta SMS_{PPT}$
3.  $ET = MAX_{SMS} - MIN_{SMS} + \Delta WATER\ TABLE$
4.  $RO = PPT - ET$
5.  $RI = ET - PPT$

Figure 20. Equations used to estimate evapotranspiration from soil-moisture data. ET = evapotranspiration, MAX<sub>SMS</sub> = maximum soil-moisture storage, MIN<sub>SMS</sub> = minimum soil-moisture storage, SMS<sub>PPT</sub> = change in storage caused by seasonal precipitation events, WATER TABLE = seasonal changes in water table levels, RO = runoff, and RI = run-in moisture.

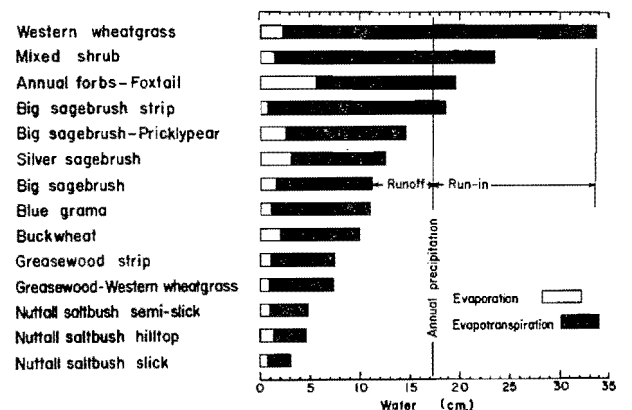


Figure 21. Measured evapotranspiration and estimated evaporation for 14 plant communities (from Branson, et al., 1970).

measured runoff of 11.5 percent. Possible errors in the method, in addition to adjustments for watershed area, include interception losses, snow sublimation losses, and surface-storage losses. Losses to groundwater in these predominantly clayey soils were considered negligible but may not have been zero.

Another example of evapotranspiration computed from soil moisture measurements is shown in Figure 23. Probably because of lower precipitation in this area, 230 mm (9 in.) as compared with 305 mm (12 in.) for communities shown in the previous graph, the range of values is not as great as is shown in the previous graph. Evapotranspiration here was significantly correlated with percent bare soil ( $r = -0.78^{**}$ ) and with percent live cover ( $r = +0.84^{**}$ ). Two communities were believed supplied with groundwater (greasewood and rubber rabbitbrush) but no fluctuations in water-table levels were detected. Thus the data shown probably represent underestimates of evapotranspiration for these communities. Either groundwater was not being used by these communities or there was constant lateral groundwater inflow to supply demand. High permeability (soil saturation percentage of about 30) and possibly snow entrapment contributed to the high evapotranspiration value for the spiny hopsage (*Grazya spinosa*) community.

A number of plant communities and habitats, some having water tables at various depths, were studied in Ruby Valley, Nevada. In computing water evapotrans-

pired, water contained in the soil at the end of the growing season is subtracted from water contained at zero stress for the depth of water table fluctuation. This is added to the quantity determined by differences in maximum wet and maximum dry conditions to obtain total evapotranspiration. For sites having very shallow water tables, i.e., those with free water at the surface in the spring, our method gave obvious underestimates of evapotranspiration. Evapotranspiration estimates for habitats with water

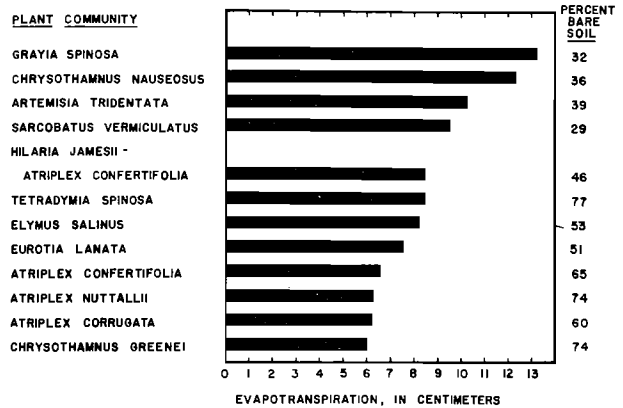


Figure 23. Relative quantities of water evapotranspired and percent bare soil for 12 northern desert shrub communities near Grand Junction, Colo. (from Branson, et al., in press).

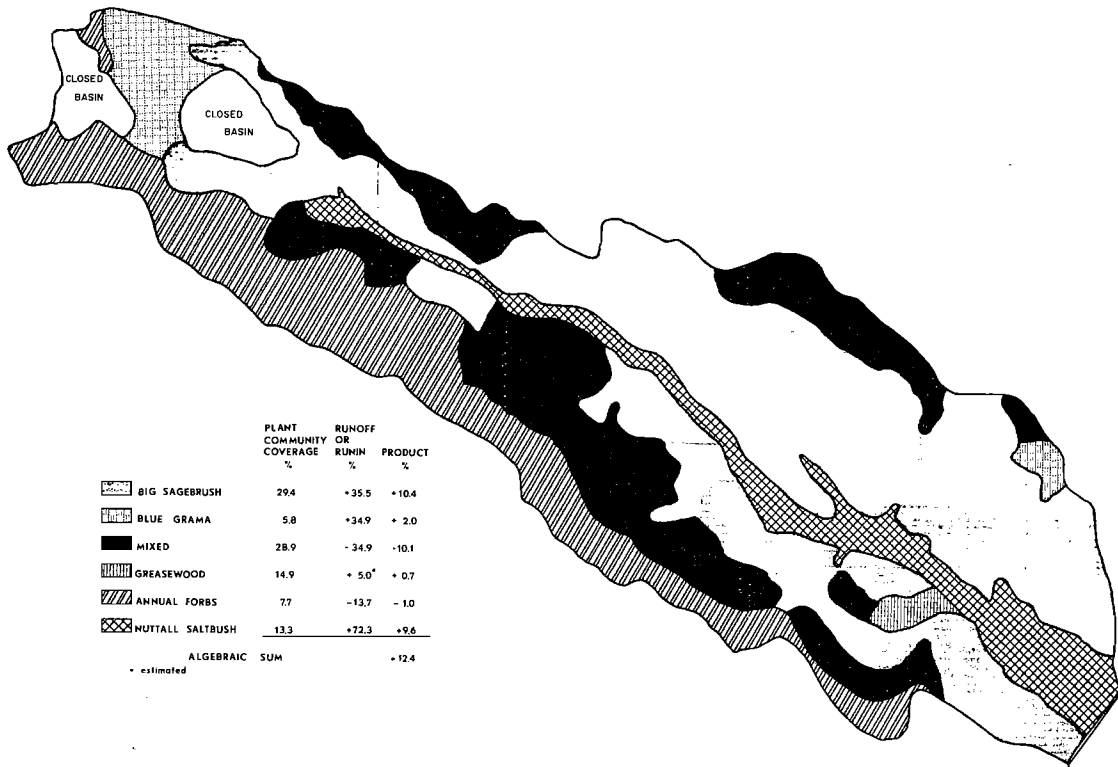


Figure 22. Plant community distribution within a watershed in northeastern Montana and calculations of estimated runoff as percentage of annual precipitation.

tables at 60 or more centimeters depth in the spring appeared reasonable and were included in the analyses.

For plant species in Ruby Valley, Nevada internal-plant stress was inversely correlated ( $r = -0.92^{**}$ ) with quantities of water evapotranspired (Figure 24). Stated differently, where water is more readily available, more water is used and plant stresses are lower. Live plant cover was positively correlated ( $r = 0.85^{**}$ ) with quantities of water evapotranspired.

**Plant Growth and Water Use**

Cumulative seasonal water use and plant growth for five northern desert shrubs are shown in Figure 25. The growth and water-use curves for rubber rabbitbrush (*Chrysothamnus nauseosus*) differ from those for the other four species. Water use before plant growth in this habitat is attributable to evaporation or possibly some additional loss by lenticular transpiration. However, the general parallelism of the two curves for this species indicates more efficient water use per increment of plant growth than was true for the additional, more drought-tolerant species.

The additional species show an increasing disparity between water use and plant growth. Stated differently, water-use efficiency becomes lower as total growth by the various species becomes less. These results lead to the conclusion that drought-tolerant species are not efficient users of soil moisture, at least in terms of plant growth per unit of water used. Admittedly, the habitats of the five species differ greatly, especially in terms of soil textures and water availability. The decreases in plant growth and water use shown are accompanied by increases in bare soil which causes the evaporation component of evapotranspiration to become larger. Although amount of bare soil, and associated evaporation, might cause the results shown,

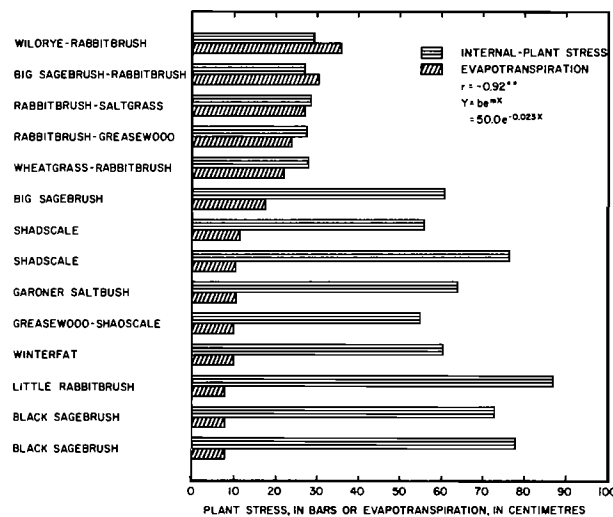


Figure 24. Internal-plant stress as related to evapotranspiration by 14 plant communities in Ruby Valley, Nevada (from R. F. Miller, written commun. 1975).

some available data tend to refute this assumption. For example, the mat saltbush soil although very salty (extract electrical conductivity of 16.7) was always moist (minimum soil-moisture stress did not exceed 10 bars during the growing season). In contrast, in soils occupied by nuttall saltbush, with similar growth and water-use curves, minimum soil-moisture stress exceeded 80 bars. These results suggest that plant characteristics determine water-use efficiency. Nevertheless, the almost immeasurably small annual increment of growth for *Atriplex corrugata* remains puzzling.

**WATER HARVESTING**

As defined by Myers (1964), water harvesting is the process of collecting precipitation from land that has been treated to increase runoff from rainfall and snowmelt. More recently (Courrier, 1973) defined water harvesting as "the process of collecting natural precipitation from watersheds for beneficial use." The latter definition is used herein because such ancient domestic practices as

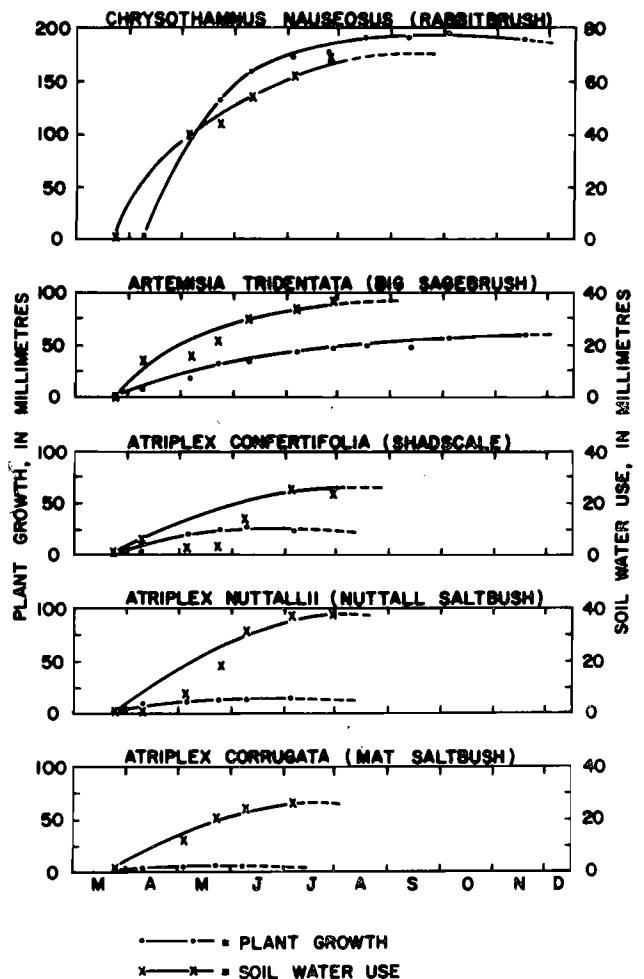


Figure 25. Seasonal plant growth and associated water use for five shrub species (from Branson, et al., in press).

collecting water from rooftops would be included if rooftops and elevated catchments could be termed "watersheds."

In the United States these developments or structures have received various names including rain traps, catchment basins, paved drainage basins, trick tanks, and guzzlers. Additional terms from Australia are roaded catchments and flat batter tanks.

Inadequate water supplies may limit range use by livestock and game. Insufficient water developments can result in overuse of range near existing supplies and underuse of range distant from water. Also, quality of existing supplies may be unsuitable for livestock because of high salt content or toxic elements. In some areas, groundwater is present at such depth that it is uneconomical to develop wells. For all of these problem areas, water harvesting might provide a solution.

### History

Water harvesting is relatively new in the United States, but developments that qualify as water harvesting date almost to the beginning of civilization. The considerable population of the Negev Desert in Israel 2,000 years ago, and probably as much as 4,000 years, in an area receiving about 4 inches annual precipitation was made possible by using water harvesting techniques (Evanari et al., 1961). To decrease infiltration and increase runoff, stones were removed from the soil surface of small-watershed slopes. Runoff from treated areas was diverted by ditches to lower lying fields where water was used to irrigate crops and fill cisterns for domestic use. Water harvesting is also thought to have been used as early as 4,500 B.C. by the people of Ur (Frasier, 1974) and has been documented in many other parts of the "old world."

### Water Harvesting Methods

Materials used to improve runoff from catchment surfaces are generally of two classes, either mechanical or chemical, with a possible third category being a combination of mechanical and chemical. Many new substances and techniques will probably be used in the future but a classification of most that have been used is as follows:

#### A. Mechanical methods:

1. Removal of stones and building trenches to collect hillside runoff.
2. Removal of vegetation plus shaping and compaction of water-collecting areas.
3. Use of iron sheets and corrugated metal roofing. Other similar materials include plastic films or sheets, butyl rubber sheets, alumi-

num foil sheets, and heavy-weight roofing paper.

4. Water collection and storage from naturally impermeable ("slickrock") areas.
5. "Roaded catchments" and "flat batter tanks" in Australia—techniques which place sub-surface clays on the surface to improve runoff.

#### B. Chemical methods

1. Some of the many chemicals used to decrease infiltration include: waxes such as paraffin, salts (Na Cl, Ca Cl, etc.), latex, heavy oils, sodium rosinate, dialkyl quarternary ammonium chloride, metallic soaps, fatty amine acids, sodium methyl silanolate, and silicones.
2. Various formulations of asphalt including asphalt treated jute, asphalt-fiberglass, and asphaltic emulsions.
3. Soil cement about 4 inches thick.

### Water Harvesting Designs

Many designs have been used but nearly all have three components: (1) A water-collection area or apron; (2) a storage tank or pit, and (3) a watering trough with automatic float valve (Figure 26). A somewhat different design is referred to as a "trick tank" (Pearson et al., 1969). Trick tanks consist of an elevated roof which serves as both collection area and shade for livestock. Other features, storage tank and watering trough, are similar to that described above.

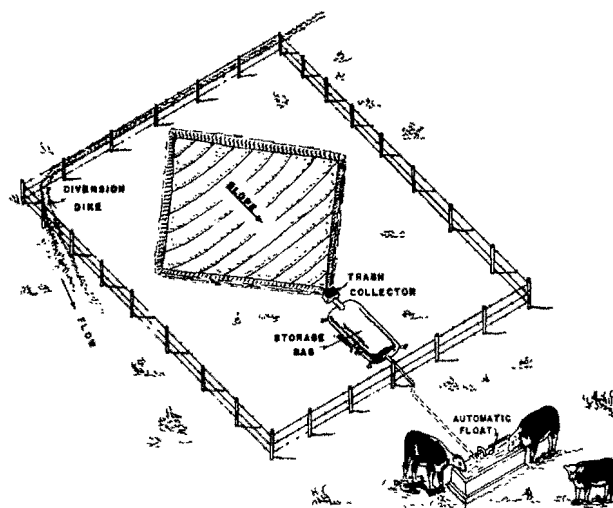


Figure 26. Features of a water harvesting system (from Lauritzen, 1961).

Collection areas should be large enough to provide the amount of water needed. Variables to consider include annual precipitation, permeability of the collection apron, and expected evaporation from collection surface, storage facility, and trough. Along a 10-inch (254 mm) precipitation isohyet, 1-yd<sup>2</sup> (0.84 m<sup>2</sup>) should yield 56 gal (212 l) of water without losses. The storage facility should be large enough to contain about 2-years water supply for carryover in dry seasons (McBride and Shiflet, 1974).

### Performance of Materials

All artificial catchment surfaces are subject to various kinds of damage and periodic maintenance efforts are required for optimum performance. Damage may result from large mammals, mainly puncturing of surfaces, if fences are not maintained. Rodents may also create holes by gnawing and burrowing. Damage may also result from plant growth, insects, vandalism, wind action, and material failure due to oxidation, ozone attack, and tearing (Dedrick, 1973). Ultra-violet radiation is damaging to both rubber and plastic. Possible solutions to these problems include: the use of soil sterilants before aprons are installed to control plant punctures, proper fencing, the use of open storage in snow areas to prevent storage bag failure due to snowpack, rodent repellents and barriers, reinforced materials to prevent tearing (ozone damage occurs only when material stretches), the use of materials not subject to oxidation such as butyl rubber, and the use of gravel layers to protect plastic films.

Estimated longevity of various materials is presented in Table 1. Although more expensive initially, more

durable materials may be a more economical investment over time. Runoff as percent of precipitation may also be important because smaller catchments can be used when surfaces are less permeable.

Water harvesting has advantages and disadvantages. Some of these have been stated earlier but some of the advantages can be listed as follows:

1. It may be the only practical means of developing water in certain areas.
2. It does not require a legal "right" for development in most areas.
3. It is usually less expensive and more convenient than hauling water.
4. It does not add to energy shortage or water pollution problems.
5. There are no "dry holes."

High initial and maintenance costs of developments may be disadvantageous in some areas, particularly where drilling wells is inexpensive.

### Additional Application of Water Harvesting

In Montana (Hodder et al., 1970) used plastic-covered small basins for tree and shrub plantings. These served as "condensation traps," directing condensed water down-

**Table 1. Runoff efficiency estimated longevity, and initial costs of various surface treatments.**

Material and Geographic Area	Runoff as Percent of Precipitation	Estimated Life of Treatment, Years	Initial Treatment Cost in Dollars/m <sup>2</sup>	Source of Data
Land clearing (Arizona)	20-30	5-10	0.01-0.02	Frasier, 1974
Land clearing (Israel)	21	—	—	Tadmor and Shanan, 1969
Soil smoothing (Arizona)	25-35	5-10	0.04-0.06	Frasier, 1974
Silicone water repellents (Arizona)	50-80	5- 8	0.0 -0.15	Frasier, 1974
Paraffin wax (Arizona)	60-90	5- 8	0.25-0.33	Frasier, 1974
Paraffin wax (Arizona)	92	—	0.10-0.15	Fink et al., 1973
Concrete (Arizona)	60-80	20	1.67-4.20	Frasier, 1974
Gravel-covered sheeting (Arizona)	70-80	10-20	0.42-0.58	Frasier, 1974
Gravel-covered sheeting (Wyoming and Colorado)	45	—	—	Rauzi et al., 1973
Asphalt-fiberglass (Arizona)	85-95	5-10	0.83-1.67	Frasier, 1974
Asphalt roofing (Wyoming and Colorado)	100	—	—	Fauzi et al., 1973
Butyl rubber (Arizona)	90-100	10-15	1.67-2.50	Frasier, 1974
Butyl rubber (Arizona)	100	—	2.39-3.59	Fink et al., 1974
Sheet metal (Arizona)	90-100	20	1.67-2.50	Frasier, 1974
Sheet metal (Colorado)	57	—	—	Mickelson, 1974
Bentonite (Colorado)	19	—	—	Mickelson, 1974
Salt treatment (NaCl) (Wyoming and Colorado)	25	—	—	Rauzi et al., 1973
Natural cover (Colorado)	5	—	—	Mickelson, 1974
Natural cover (Arizona)	28	—	—	Fink et al., 1973
Natural cover (Israel)	7	—	—	Tadmor and Shanan, 1969

ward towards the seedlings and probably trapped precipitation in a similar manner. In New Mexico, Aldon and Springfield (1974) used 4-ft<sup>2</sup> plots of wax and 4 mil. black polyethylene to increase survival and growth of four-wing saltbush seedlings. Runoff increase was 40 percent for paraffin and 34 percent for polyethylene.

Reduction of water losses caused by evaporation may also be considered water harvesting. Covered storage tanks and butyl rubber water storage bags control evaporation. Extensive tests with monomolecular films on stock reservoirs (Koberg et al., 1963) have not shown satisfactory results and have led to the use of more durable materials. Floating sheets of foam rubber, 3/16 in. thick have been used in Utah (Dedrick et al., 1973) to reduce evaporation loss from stock tanks. There were some problems encountered in the use of the material (pecking by birds, temporary clogging of bailing holes, and separation of the cover by ice) but none of these problems caused failure. The material is expensive (cost was \$1.80 to \$2.00 per 1,000 gal of water saved) but may be justifiable when compared to alternate means of producing or saving water.

Seepage losses from reservoirs may equal or exceed evaporation losses. Many of the techniques used for rainwater harvesting can also be used to prevent seepage losses. Some of these include: soil compaction, chemical treatment of soil, and soil covers such as butyl rubber, sheet plastic, asphalt reinforced with plastic or fiberglass, and ferrocement (National Academy of Science, 1974).

Calcium aggregated clays sometimes cause reservoir seepage. Chemicals such as sodium carbonate have been used to reduce seepage from reservoirs containing clay soils. Bentonite has been used to "seal" reservoirs having porous soils. If plastic or rubber sheeting is used, protection from livestock damage by fencing or soil covering is necessary.

## WATERSPREADING

Waterspreading is the technique of diverting runoff water from ephemeral stream channels onto suitable areas to increase groundwater recharge or plant growth (figure 27). Use of the technique is ancient. It is believed to have been used in the Negev Desert of Israel as early as 4,000 years ago (Evanari et al., 1961) and reached sophisticated development by the Nabataens and Romans in the Negev 2,000 years ago and by the Romans in North Africa at about the same time (Lowdermilk, 1953). In southeastern Montana, some waterspreaders on privately-owned land have been in use for nearly 80 years. Much earlier use in this country was by Indians of the southwestern United States some 500 years ago (Meyers, 1974).

Some of the ancient systems in the Negev Desert have been rehabilitated and are again in use (Evanari et al.,

1971) and numerous spreaders have recently been built in other arid and semi-arid lands (French and Hussain, 1964).

Many waterspreaders were constructed on public lands following the drought and depression years of the 1930's. Most of these were included in an evaluation study by Miller et al. (1969).

Range waterspreader construction has two main objectives: (1) Increasing forage production by diverting flow from ephemeral channels, and (2) reduction of gully erosion and downstream flooding. Because of the ephemeral nature of flood flows and the usual remote locations of range spreaders, they are designed to function automatically.

## Waterspreader Systems

Designs vary from very simple dams ("gully plugs") that divert water from stream channels onto flood plains (Hadley and McQueen, 1961) to complex systems that include detention or retention dams, training or diversion dikes, and spreader dikes (Stokes et al., 1954). Generally, spreaders are designed to fit local conditions. Numerous designs are discussed by Stokes, et al. (1954).

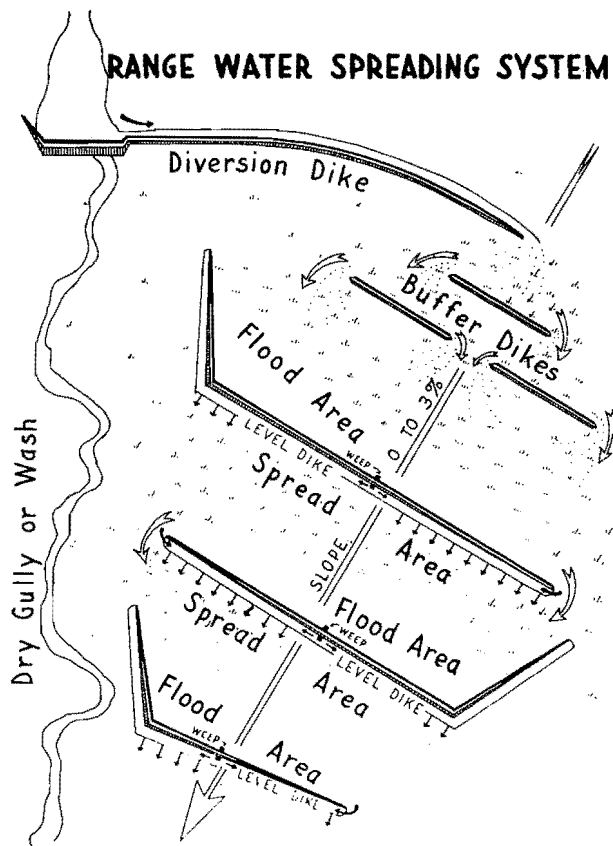


Figure 27. Diagram of a range waterspreader (from Branson, 1956).



Water supply is a critical factor in spreader design. The catchment area should yield at least enough water for one complete spread per year but the flow should not be so large as to be unmanageable. Detention reservoirs with water release controlled by outlet tubes may be preferable to simple diversion dams for water control. Getting water off the spreader is almost as important as adequate supplies for spreading. Prolonged ponding of water on spreaders causes reductions in forage yields or the growth of less desirable hydrophytic vegetation. Excessive ponding can be a problem even on coarse-textured soils but occurs more frequently on fine textures (Miller et al., 1969). Best results have been obtained on medium and medium-fine textured soils.

Because of water-supply problems, construction of waterspreaders in areas of less than 8 in. (200 mm) is not generally recommended. However, the carefully designed, ancient spreaders of the Negev Desert helped sustain a fairly dense population in an area receiving only 4 in. (100 mm) annual precipitation (Evanari et al., 1961). In the Negev it was necessary to improve runoff from catchments by removing stones from the soil surface and to construct ditches to divert water to spread areas. Such expenditures in labor would not be considered economical in our culture.

Continued maintenance is essential for proper functioning of waterspreaders. If the original design is faulty, corrections must be made. Problems are fewer on spreaders with controlled inflow of water but these also are often damaged by intense rainstorms. When repairs are necessary, design modifications such as additional drains through dikes can be installed to improve performance of the waterspreader.

Sediment deposition has been a problem on some spreaders but in a few instances such deposition has been beneficial. Usually, because of reduction in flow velocities as compared with original stream channel velocities, finer sediments than those present before spreading are deposited. If the spreader area has coarser than optimum soils, deposition of finer particles may be beneficial. Excessive sediment deposition can often be avoided by constructing sediment barriers at the upper end of diversion reservoirs.

Reported forage production increases have varied from 300 to 1,000 percent on areas flooded (Branson, 1956; Houston, 1960; Hubbell and Gardner, 1950; and Monson and Quesenberry, 1958). However, a few spreaders have been constructed in areas where water supply was so minimal that little or no increase in forage occurred.

Costs of construction and maintenance of waterspreaders has also varied greatly. Simple diversion dams of "gully plugs" are relatively inexpensive per unit of spread area. On more complex systems, costs (1955 prices) ranged from less than \$1 to as high as \$20 per acre (Pierson, 1955). Costs of maintenance has ranged from

almost nothing on some spreaders to \$6.55 per acre (Branson, 1956).

## WATER MANAGEMENT

Water yields may be increased or decreased and water quality affected beneficially or adversely by rangeland treatment practices. We now know a great deal about the hydrologic responses of land to treatment practices but it is only in relatively recent times that downstream water users have begun to consider upstream land treatment to increase water delivery rates. This development leads to some interesting questions. Should arid-zone water managers try to maximize forage yields in upland watersheds or increase downstream water yields by diminishing forage yields or other practices that decrease infiltration and increase runoff? Does downstream use of water produce more for human good than upstream use? What are the aesthetic effects of converting woody vegetation to herbs for water-yield increases? Of course, there are the legal and environmental questions about upstream activities that affect quantity and quality of water delivered downstream.

These and similar questions are being asked and the demands for answers will increase in the future. Competition for the water resource from rangelands is increasing. In certain states (e.g., New Mexico and Arizona) the application of range practices such as waterspreading are being prevented because of water demands by downstream irrigators. In Oregon irrigation interests exert considerable control over stock-water developments on public range. Research is needed to determine whether or not water developments on upland range actually adversely affect water delivery downstream; in places the water may be largely lost by evapotranspiration along stream channels if not used on site.

Range ecologists have generally assumed that if ranges are in good to excellent condition, other products from the land such as water quantity and quality will also be "good." Although the generalization is probably true for some land products, watershed studies (Hanson et al., 1970; Lusby, 1970; and Dunford, 1949) have shown that the higher (or better) the range condition the lower the water yields. In a few instances, greatly improved ranges have resulted in dry stock reservoirs, associated underuse of range, and the need for alternative sources of water. Sediment yields show the reverse relationship, i. e., the higher the runoff the higher the sediment yields. These results lead to the question, "What is the optimal range use necessary to yield the most beneficial mix of products from rangeland?"

The many techniques used in water harvesting lead to the speculation that in the future certain watersheds may completely be modified for the single purpose of increasing water yield. Such a proposal would produce many

questions about alternatives, aesthetic effects, timber, wildlife, flood hazards, wildlife habitat, forage for livestock, and pollution. It is conceivable that demands for water in some areas for domestic, agricultural, and industrial use might take precedence over all other land values. Alternatives include reduced population growth and increased demands for environmental quality. Water requirements in the United States are expected to triple by the year 2,000 and competition for the water resource will obviously become more intense.

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## Watershed Inventory System in Use by The Bureau of Land Management

*Ronald L. Kuhlman\**

As early as 1969 the Bureau of Land Management recognized a need to identify the location and magnitude of watershed problems associated with erosion, water quantity and water quality. This had never been attempted on the 170,300,000 acres (68,900,000 hectares) to be inventoried under BLM administration in the contiguous states. A systematic procedure for the conduct of such an inventory to identify watershed problems in arid and semi-arid areas was sorely needed.

The objectives for the inventory were determined to be: (1) Identify watershed problems and suitable treatments; (2) provide this information to the Bureau planning data bank; (3) provide criteria by which a land manager can consider the magnitude of watershed problems and needs in planning all resources (wildlife, range, forestry, lands, recreation and minerals); and (4) provide a range of alternative courses of action for problem solving.

To meet these objectives, data are collected on WATERSHED AREAS which are geographic areas, not necessarily natural drainages. The surface administration of the watershed areas was designated as either BLM or other, dependent on responsibility. It was necessary to do this because of the complex land ownership in parts of the area to be inventoried. Generally, a single watershed area represents 20 to 30 square miles (5,200 to 77,700 hectares). Data collection points were established at an average density of one per 2,000 acres (800 hectares).<sup>1</sup> All data collection points are placed on maps and identified by vegetation and aspect. The attached form, Figure 1, Watershed Conservation and Development Field Data, is completed on the basis of existing data and supplemented by field work. The completed forms are entered into computers for processing to provide various printouts needed to meet objectives 1 and 2. These printouts provide

the identity of watershed problems and treatments in a format suitable for input into the Bureau planning process.

Copies of the data are available for special studies from Bureau of Land Management.

Section I of Figure 1 contains general watershed area descriptions including information on flooding and water quality. This information is very general and simply serves as an indicator of areas when additional data are required if a problem in flooding or water quality is indicated.

Section II refers to vegetal subtype and water yield data. There are 61 vegetal subtypes that can be identified. All data are entered with a vegetal subtype identifier in order to provide the opportunity to identify problems associated with a particular vegetation. For example, erosion activity, soil depths, slopes, aspects, percent ground cover and opportunities for improvements may all be studied by vegetation subtype. In addition, data are requested on potential vegetative productive capacity under natural conditions plus an estimate of the opportunities for increasing water yield. Water yield increases for off-site use are not estimated if the annual precipitation is less than 17 inches. A review of research indicates that the type of land treatment normally applied by BLM does not increase water yield. In fact, changes in vegetation composition to control erosion are likely to decrease water yield because of additional evapotranspiration by the added plants. Water yield for off site use is a very minor source from lands administered by BLM. For example, of the 1700 watershed areas inventoried by January 1975 less than 20 were considered to have a potential for increases in water yield for off-site use. Even on these, the estimated total water yield was less than 15,000 acre feet.

Section III refers to transect data. These data are recorded while on location. They consist of transect identification, ground cover, soils, soil surface factors (erosion), and potential treatments. Page 2 of Figure 1 gives a detailed listing of these data for your information. Two of these factors, Effective Root Depth (column k) and Soil Surface Factor (columns o, p, q, r) may not be familiar to you.

\*Chief, Division of Watershed, Bureau of Land Management, Washington Office.

<sup>1</sup>The inventory procedures are described in Bureau Manual Section 7322.1, Release No. 7-53, September 26, 1973. A complete description of the inventory procedures is available upon request to the Bureau of Land Management, Attention Watershed Staff, D-350, Building 50, Denver Federal Center, Denver, Colorado 80225.



SECTION III - TRANSECT DATA (FORMAT B)

LINE	TRANSECT IDENTIFICATION			PERCENT OF GROUND COVER					SOIL			SOIL SURFACE FACTOR			TREATMENTS								
	(10-11) PLANNING UNIT	(12-14) VEGETAL SUBTYPE	(15) EXPOSURE	(16-17) NUMBER	(18-19) PERCENT OF VEGETAL SUBTYPE	(20-21) VEGETATION	(22-23) LITTER	(24-25) SMALL ROCK	(26-27) LARGE ROCK	(28-29) BARE GROUND	(30-31) EFFECTIVE ROOT DEPTH	(32) TEXTURE	(33) TEXTURE	(34-35) PERCENT OF SLOPE	(36-37) PRESENT	(38-39) WITHOUT MANAGEMENT CHANGE	(40-41) LAND USE MANAGEMENT CHANGE	(42-43) WITH ADDITIONAL TREATMENTS	(44) CHEMICAL	(45) MECHANICAL	(46) WATERSHED TILLAGE	(47) WATER CONTROL	
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	(n)	(o)	(p)	(q)	(r)	(s)	(t)	(u)	(v)	
1	16	041	2	1	45	40	10	5	9	36	22	3	4	6	40	42	29	22	✓	✓	-	-	
2	05	041	5	2	5	35	11	6	0	40	22	2	3	2	45	46	20	20	✓	-	-	-	
3	16	041	1	3	50	19	12	8	11	50	22	3	4	10	45	50	45	30	-	-	-	-	
4	16	091	4	1	65	26	10	5	7	62	14	3	4	35	52	47	52	30	-	-	-	-	
5	16	091	2	2	35	19	0	0	5	60	14	3	4	20	52	52	62	25	-	-	-	-	
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Figure 1. Part 2.

Form 7330-12a  
(May 1973)

UNITED STATES  
DEPARTMENT OF THE INTERIOR  
BUREAU OF LAND MANAGEMENT

WATERSHED CONSERVATION AND DEVELOPMENT FIELD DATA  
INSTRUCTIONS

GENERAL INSTRUCTIONS

Check photocopy for legibility prior to submission. District Office prepares in *duplicate*. Submit original to State Office. File copy in District Office. Copy may be destroyed after verification of data on ADP printout except for *Remarks* needed for future use.

SPECIFIC INSTRUCTIONS

(Items not listed are self-explanatory)

The following must be completed prior to field work:

- Section I, Items 2 through 11;
- Section II, Columns (a) through (e); and
- Section III, Columns (a) through (e)

*Item 1 - Transaction Code* - For data corrections make photocopy of original submission, correct in red pencil, and submit to ADP for processing. For data deletion, complete items 2, 3, and 4 and submit to ADP. This is desirable when watershed areas are combined or major errors have been made on prior submissions.

*Items 2 & 3 - State & District* - Code according to BLM Manual 1265.

*Item 4 - Watershed Area (WA)* - Code numbers 001 through 699 in numerical sequence until complete district has been covered.

SECTION I - GENERAL WATERSHED AREA DESCRIPTION

*Item 5 - County* - Code according to BLM Manual 1265. Use only dominant county for each WA.

*Item 6 - Sub-basin* - Code according to BLM Manual 1265. Use only dominant sub-basin.

*Item 7 - Total Acres* - Include all acres, BLM and Other, for all Planning Units in this WA. Must equal total of Section II, Columns (d) and (e). Normally, between 20 and 400 sq. mi.

*Item 8 - Name of Watershed Area* - Give local name of area being studied.

*Item 9 - Annual Precipitation* - Record a single value for each WA. Obtain from isohyet maps or other data that represent watershed areas such as precipitation gauges.

1. *Gauged Data* - Use gauged data when it provides better quantification. Usually individual gauges having less than 10 years of record will not give reliable quantification of average precipitation but may be used if best available information. Identify by footnote giving source of data.
2. *Variance of Precipitation* - In WA having significant variation of average precipitation, use care to provide a representative WA value. Determine a weighted value, the same as weighted values are computed for root depth and soil surface factor. Annual precipitation should not vary more than  $\pm 5$  inches from average precipitation for WA on more than 10 percent of area.

*Item 10 - Month of Peak Flow* - Month normally experiencing peak runoff events exclusive of snowmelt and rain on snow events. Indicates what can be done by vegetal manipulation to reduce peak flow.

*Item 13* - Refers to origin of runoff which produces flood. Identify origin in terms of State, District, and WA; include those areas not under administration of Bureau by using WA No. 700-999.

*Item 14 - Agriculture* refers to all types of agricultural damages. *Urban* refers to city damages to homes, yards, gardens, etc. *Public* refers to roads, bridges, and all public property. Not included is erosion or other flooding damage on public domain. *Industrial* refers to business and industrial improvements.

*Item 17* - Give location or general area where problem originates. If not administered by BLM, use WA numbers 700-999. WA must be identified by State, District, and WA numbers.

*Item 18* - This is to identify water use having a water quality problem and its relative intensity. More than one purpose may be indicated. Uses indicated must have an intensity letter associated with them. Spaces are to be used to identify any other use in less than 21 letters.

*Item 19 - Private land use* refers to those which cause problems for BLM. *Public purposes* refers to highway and utility maintenance.

SECTION II - VEGETAL SUBTYPE  
AND INCREASE USABLE WATER YIELD

*Column (a) - Planning Unit* - Code according to BLM Manual 1265. Enter code for each subtype listed in Column (b) representing the Planning Unit.

*Column (b) - Vegetal Subtype* - Enter subtype for each Planning Unit. Barren areas and cropland must also be entered. All entries must be in numerical sequence - 011 to 191 for each Planning Unit.

Code according to BLM Manual 1265. Identify all subtypes comprising more than five percent of area. Usually six subtypes are sufficient.

Seedlings that have not reached their ultimate growth under management and compose more than five percent of area are considered as part of the subtype existing prior to treatment. Area designated as 07 on Range Survey maps are identified by specific reason as shown in BLM Manual 1265. Areas designated as 08 on Range Survey maps may not contain transect locations.

*Column (c) - Productive Capacity* estimate of average total vegetal production over a 10+ year period. This item optional.

Acres provide area by Planning Unit and Vegetal Subtype for both BLM and other. Total of Columns (d) and (e) must equal Item 7.

*Column (d) - BLM* - All BLM acres of the subtype.

*Column (e) - Other* - Acres other than BLM in subtype that are significantly affected.

*Column (f) - Number of Transects* completed within a particular vegetal subtype. No transects are to be located in the 08 or 191 subtypes.

Figure 1. Part 3.

WATER MANAGEMENT IMPROVEMENT

*Increased Usable Water* is defined as water made available for use. Additional ground water recharge is considered an increase in usable water yield. Columns (g), (h), and (i) must be completed to obtain WRP2. Does not apply to areas with < 17" precipitation.

*Column (g) - Potential Acres* - Acres by subtype and Planning Unit yielding Column (h). These are the only acres modified.

*Column (h) - Ac.Ft.* - Average annual increase of usable water made available by Bureau protection, development, or management practices. Enter value for each line identified in Column (g).

*Column (i) - \$/Ac.Ft.* - Value a water user would pay for additional water based on market value for comparable purposes in same area. Enter value for each line identified in Column (h).

*Column (j) - Treatment Class* - Check method(s) of increasing usable water. ADP printout will show M for management, C for chemical, and T for mechanical treatment.

SECTION III - TRANSECT DATA

*Columns (a), (b), (c), and (d) - Transect Identification* - On field data collection, these items should be completed prior to field work. Cover data for each transect may be obtained from Form 7310-10 (*Ground Cover Transect Data Sheet*). Caution should be used to ensure that data are transferred to same line in Section III. Each transect must represent less than 6400 acres unless up to 10,000 acres is authorized by State Office.

*Column (b) - Vegetal Subtype* - See Section II, Column (b).

*Column (c) - Exposure* - Applies to general topographic exposure of area represented by transect. Code as follows: 1 - north; 2 - east; 3 - south; 4 - west; and 5 - flat. Those areas having less than one percent slope are recorded as 5.

*Column (d) - Number* - Transects within subtypes are numbered consecutively, lowest to highest, from top to bottom of page.

*Column (e) - Percent of Vegetal Subtype* - Estimate within five percent by subtype and planning unit, the actual area transect represents in particular subtype. Must total 100% for each vegetal subtype within each Planning Unit.

*Columns (f) through (j) - Percent of Ground Cover* is summary of 100 hits recorded and totaled on Form 7310-10. These columns must total 100% per line entry.

*Column (k) - Effective Root Depth* - Excavate soil pit next to plant to a depth of 25 inches or to restrictive layer (hardpan, caliche, bedrock, etc.). Measure distance from soil surface to obvious transition zone from common to few roots

to obtain ERD. If restrictive layer is encountered and roots accumulate on surface of restrictive layer (no transition zone is obvious), effective root depth is distance from soil surface to restrictive layer. In soils developed from shale, measure to beginning of the partially weathered shale layer (no transition zone is obvious).

*Columns (l) and (m) - Soil Texture* - Are recorded at two separate depths, 1/4" to 4" and 4"+ to effective root depth of 25". Code according to BLM Manual 1265.

*Column (n) - Percent of Slope* - The general slope for total area. Soils and slope information, when considered together, serve as an indication of potential mechanical treatment for area.

SOIL SURFACE FACTOR

*Column (o) - Present* - Obtain from Form 7310-12.

*Column (p) - Without Management Change* - Without change in present management in the next 15 years. May be higher on deteriorating sites compared to present or lower for improving sites.

*Column (q) - Land Use Management Change* - With desirable changes of all types; people, timber, livestock, etc. Reflects the potential Soil Surface Factor expected 15 years after management changes are initiated.

*Column (r) - With Additional Treatment* - Reflects potential effect of management and treatment on soil stability.

TREATMENTS

Refers to general treatments used to attain SSF. Indicate with check.

*Column (s) - Chemical* - All chemical applications for manipulating vegetation - ADP printout C.

*Column (t) - Mechanical* - For plowing, churning, rilling, top or root cutting, blading, or harrowing - ADP printout T.

*Column (u) - Watershed Tillage* - For contouring, ripping, terracing - ADP printout W.

*Column (v) - Water Control* - For detention and retention dams, drops, diversions, dikes, water-spreaders, and canals - ADP printout A.

REMARKS

Give particular situations that may affect data presented.

Remarks should also be made concerning management and treatment situations as they affect data collected. These will assist in projecting future conditions on similar areas under a similar management and treatment.

Figure 1. Part 3. (Continued).



BLM uses Effective Root Depth as an indicator of the portion of soil profile from which a plant received the majority of moisture and nutrients for annual growth. Our experience on arid and semi-arid lands indicates that this depth seldom reaches more than 25 inches. The limiting factor on plant development in these areas is moisture which controls both the plant growth and soil development.

The second factor, Soil Surface Factor (SSF), is obtained from observations of surface features at the time data are collected. Figure 2 describes the observations quantified in this process. Estimates of future soil surface factors are based on observed conditions on similar soil-vegetation units under various treatments in the general area of the inventory.

These data are then manipulated through a set of formulas to determine a single mathematical expression called a Watershed Rating Point as shown in Figure 3. The range is predominantly between 500 and 3000 with a median of 1464 points on a population of 1040 samples.

Current and projected erosion conditions are available from the inventory data on several geographic areas: 10 states; 54 districts; 640 planning units; 1700 watershed areas.

By 1978, the inventory will be essentially completed. At that time, BLM expects to have data on approximately 2200 watershed areas covering 170,300,000 acres.

For clarity of the descriptive terms in Table 1, the PRESENT refers to the time of field work which may be any time between 1971 and 1975. FUTURE refers to a point 15 years from present under the assumption that no changes in management, use or treatment occur. WITH MANAGEMENT refers to 15 years from present assuming the application of management was initiated at the present time. This considers all forms of management (livestock, wildlife, off-road vehicles, recreation, etc.) to meet normal management objectives for each resource. It is conceivable that management decision for a given resource may increase erosion on a particular area. For example, if livestock management plans require utilization of the vegetation for forage when it is needed to protect the soil surface from erosion. The result will be increases in sediment delivered to the stream system.

**Table 1. Percent distribution of erosion condition on natural resource lands as of May, 1975.**

	Stable	Slight	Moderate	Critical	Severe
ARIZONA 11,900,000 acres; 8,500,000 acres completed					
Present	5	58	30	6	1
Future	5	57	29	8	1
With Mgt	6	66	24	4	0
With Mgt & Treatment	9	70	18	3	

**Table 1. (continued).**

	Stable	Slight	Moderate	Critical	Severe
CALIFORNIA 18,200,000 acres; 5,300,000 acres completed					
Present	12	53	31	4	0
Future	12	51	32	4	0
With Mgt	22	48	26	4	0
With Mgt & Treatment	26	45	25	4	0
COLORADO 7,900,000 acres; 2,600,000 acres completed					
Present	7	28	54	11	0
Future	6	28	55	11	0
With Mgt	10	48	37	5	0
With Mgt & Treatment	13	72	13	2	-
IDAHO 11,000,000 acres; 5,900,000 acres completed					
Present	16	49	31	4	0
Future	15	46	32	7	0
With Mgt	32	51	15	2	0
With Mgt & Treatment	42	48	10	0	0
MONTANA 8,100,000 acres; 2,600,000 acres completed					
Present	18	51	21	8	2
Future	18	46	20	14	2
With Mgt	31	51	11	6	1
With Mgt & Treatment	34	49	10	6	1
NEVADA 47,300,000 acres; 34,100,000 acres completed					
Present	5	57	34	4	0
Future	4	45	44	7	0
With Mgt	10	64	24	2	0
With Mgt & Treatment	15	64	19	2	0
NEW MEXICO 12,600,000 acres; 9,100,000 acres completed					
Present	9	34	37	18	2
Future	9	30	39	20	2
With Mgt	17	35	33	14	1
With Mgt & Treatment	22	49	26	3	0
OREGON 13,400,000 acres; 9,900,000 acres completed					
Present	18	57	24	1	0
Future	18	55	23	3	0
With Mgt	27	63	10	0	0
With Mgt & Treatment	44	54	2	0	0
UTAH 22,600,000 acres; 9,400,000 acres completed					
Present	4	58	29	9	0
Future	4	58	29	9	0
With Mgt	10	60	23	7	0
With Mgt & Treatment	11	64	20	5	0
WYOMING 17,300,000 acres; 7,600,000 acres completed					
Present	5	49	41	5	0
Future	4	38	44	13	1
With Mgt	11	66	21	2	0
With Mgt & Treatment	23	59	16	2	0

UNITED STATES  
DEPARTMENT OF THE INTERIOR  
BUREAU OF LAND MANAGEMENT

○ ~ Present  
□ ~ w/o Mgt. Change  
X ~ Land Use Mgt. Change  
α ~ with X plus treatment.

By RLK Date 9/10/68  
Location 27-04-003 WA  
Transect 1604121  
Treatment affecting the SSF

DETERMINATION OF EROSION CONDITION CLASS  
SOIL SURFACE FACTORS (SSF)

SOIL MOVEMENT*	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
No visual evidence of movement				α		X		⑦	⑧							
Some movement of soil particles																
Moderate movement of soil is visible and recent. Slight terracing generally less than 1" in height.																
Occurs with each event. Soil and debris deposited against minor obstructions.																
Subsoil exposed over much of area, may have embryonic dunes and wind scoured depressions																
SURFACE LITTER*	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
Accumulating in place				α		⑤										
May show slight movement																
Moderate movement is apparent, deposited against obstacles																
Extreme movement apparent, large and numerous deposits against obstacles																
Very little remaining (use care on low productive sites)																
SURFACE ROCK*	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
If present, the distribution of fragments show no movement caused by wind or water																
If present, coarse fragments have a truncated appearance or spotty distribution caused by wind or water					α	③	X									
If present, fragments have a poorly developed distribution pattern caused by wind or water																
If present, surface rock or fragments exhibit same movement and accumulation of smaller fragments behind obstacles																
If present, surface rock or fragments are dissected by rills and gullies or are already washed away																
PEDESTALLING*	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
No visual evidence of pedestalling																
Slight pedestalling, in flow patterns																
Small rock and plant pedestals occurring in flow patterns																
Rocks and plants on pedestals generally evident, plant roots exposed																
Most rocks and plants pedestalled and roots exposed																
FLOW PATTERNS*	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
No visual evidence of flow patterns																
Deposition of particles may be in evidence																
Well defined, small, and few with intermittent deposits																
Flow patterns contain silt and sand deposits and alluvial fans																
Flow patterns are numerous and readily noticeable. May have large barren fan deposits.																
RILLS	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
No visual evidence of rills																
Some rills in evidence at infrequent intervals over 10'																
Rills 1/2" to 6" deep occur in exposed places at approximately 10' intervals																
Rills 1/2" to 6" deep occur in exposed area at intervals of 5' to 10'																
May be present at 3" to 6" deep at intervals less than 5'																
GULLIES	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
May be present in stable condition. Vegetation on channel bed and side slopes																
A few gullies in evidence which show little bed or slope erosion. Some vegetation is present on slopes.																
Gullies are well developed with active erosion along less than 10% of their length. Some vegetation may be present.																
Gullies are numerous and well developed with active erosion along 10 to 50% of their lengths or a few well developed gullies with active erosion along more than 50% of their length																
Sharply incised gullies cover most of the area and over 50% are actively eroding																
SITUATION	TOTAL															
	Present SSF = 40; w/o Mgt. Change, SSF = 42; Land Use Mgt. Change, SSF = 29; with Mgt. Change & Treatment SSF = 22															

Erosion Condition Classes: Stable 0-20; Slight 21-40; Moderate 41-60; Critical 61-80; Severe 81-100

(Instructions on reverse)

Figure 2. Part 1.

## EXAMPLES

ITEM	EXAMPLE ONE			EXAMPLE TWO**			EXAMPLE THREE***		
	POTENTIALLY PRESENT	IDENTIFIED FACTORS	POSSIBLE FACTOR	POTENTIALLY PRESENT	IDENTIFIED FACTORS	POSSIBLE FACTOR	POTENTIALLY PRESENT	IDENTIFIED FACTORS	POSSIBLE FACTOR
Soil Movement	Yes	8	14	Yes	8	14	Yes	8	14
Surface Litter	Yes	9	14	Yes	9	14	Yes	9	14
Surface Rock	Yes	7	14	No	-	--	No	-	--
Pedestalling	Yes	10	14	Yes	10	14	Yes	10	14
Rills	Yes	8	14	Yes	8	14	No	-	--
Flow Patterns	Yes	10	15	Yes	10	15	Yes	10	15
Gullies	Yes	6	15	No	-	--	No	-	--
TOTAL		58	100		45	71		37	57
Total SSF		$\frac{58}{100} \times 100 = 58$			$\frac{45}{71} \times 100 = 63$			$\frac{37}{57} \times 100 = 65$	

## GENERAL INSTRUCTIONS

District prepares one (1) copy and files in district with particular study under consideration.

Do *not* include items in computations which are not potentially present.

Identify numerical factor that most nearly describes the conditions observed by circling the factor given for each logical item.

\*Wind and water are considered eroding agents when evaluating item

\*\* A soil with no rocks in its profile and no probability of gullyng

\*\*\* A pumice soil area where no water erosion occurs

## SPECIFIC INSTRUCTIONS

Total all factors at bottom of page. Divide total identified factors by total possible factors for items considered and multiply by 100 in order to compute the SSF.

*Situation* – Describe situations being evaluated such as present, geologic, with mechanical treatment in effect for 10 years, under a 5 pasture livestock management system for last 8 years, etc.

*Total* – Total computed SSF.

Figure 2. Part 2.



WITH MANAGEMENT AND TREATMENT refers to 15 years from present assuming full application of management and treatments such as mechanical or chemical vegetative manipulation, watershed tillage or water control measures.

EROSION CONDITION BY STATE can serve as the basis for several comparisons on Natural Resource Lands (NRL). From the viewpoint of the most acres of stable condition in NRL, the 10 states included in the inventory rank are Oregon, Nevada, Montana, New Mexico, Utah, Wyoming, Arizona, Colorado, and Idaho. From the viewpoint of average stability per state they rank Oregon, Montana, Idaho, California, New Mexico, Colorado, Nevada, Arizona, Wyoming and Utah. In terms of opportunities for greatest number of acres to improve through management per state, Nevada, California, Idaho, Utah, Oregon, Montana, Wyoming, New Mexico, Colorado, and Arizona. In terms of opportunity for greatest improvement possibilities by management per unit area; Idaho, Montana, California, Oregon, New Mexico, Utah, Wyoming, Nevada, Colorado, and Arizona.

At the District level, these data suggest that the most significant opportunity for reduction in erosion through management of livestock in terms of acres benefited exist in these 5 Districts: Ely, Nevada; Albuquerque, New Mexico; Lakeview, Oregon; Safford, Arizona; and Socorro, New Mexico. The data also suggest that the most significant opportunities for reduction in erosion through the application of mechanical treatments in addition to management in terms of acres benefited exist in these five Districts: Ely, Nevada; Albuquerque, New Mexico; Lakeview, Oregon; Safford, Arizona; and Phoenix, Arizona.

The significance of these comparisons is that for the first time management has a tool to compare one management area against another in the process of determining priorities to meet given objectives. It may be of even more importance to know where not to concentrate the limited management resources of funds and manpower. The use of these data has been recognized by some and has resulted in shifts in the traditional distribution of resources. They have also been used to identify where increased emphasis should be placed to solve erosion problems. This eventually results in additional funds and manpower being allocated to these areas.

#### LAND USE PLANNING

A major use of these data are in land use planning. They are used to assist in determining what the magnitude of a problem in erosion control, water quality or water yield may be. From this, it can be shown where to concentrate efforts for a solution, what approach should be used, and the most likely changes that may occur. The data are also used to make recommendations on land use based on field observations of both treated and nontreated areas.

These recommendations are submitted to decision-makers along with those of several other resource technicians as the best methods and probable effects to reduce undesirable erosion, change water yield, and improve water quality. Within the planning system, these recommendations are weighed against each other and decisions are made to meet the multiple-use needs of the particular area. For instance, the inventory data may suggest the use of chemical vegetative manipulation in order to encourage a more desirable plant growth for erosion reduction. This may contribute to a water quality problem for wildlife. Therefore, the recommendation could be modified by changing the chemical treatment to watershed tillage such as contour furrowing.

#### MAGNITUDE OF EFFECTS—EXAMPLE, ALBUQUERQUE, NEW MEXICO

The observed magnitude of treatment application under field conditions in northwest New Mexico within the Albuquerque District suggests that one-third of the area would be significantly benefited by some form of surface treatment in addition to management of livestock. Treatments that were observed and the relative effects are: Management of surface uses such as livestock management could be expected to reduce erosion by an average of five soil surface factors. When management alone would not obtain the desired effects on the vegetal cover and thereby reduce erosion, it could be combined with chemical or mechanical vegetative manipulation treatments. Use of chemical applications for manipulating vegetation could be expected to bring about a reduction in the soil surface factor of 10 or twice the management effect. Many times, field conditions are such that management alone would not affect erosion without chemical treatment. This is especially true of mesquite-dominated areas. When a mechanical treatment such as plowing, churning, rilling, tap or root cutting, blading or harrowing was appropriate, it could be expected to bring about a reduction in soil surface factor of 15 or three times that of management alone.

When an adequate vegetal type for control of surface erosion is present but at a density insufficient to attain an acceptable level of erosion the area could be treated by watershed tillage or water control measures. Where it was appropriate to apply watershed tillage practices such as contouring, ripping, or terracing, it could be expected that the soil surface factor would be reduced by 12 or two to three times that of management alone. If it were appropriate to apply water control measures such as detention dams, retention dams, diversion, dikes, water-spreaders or canals, it could be expected that the soil surface factor would be reduced by 12 or about the same as for watershed tillage.

In some instances, it is desirable to apply multiple treatments such as watershed tillage and water control. When this is done, the effects are about 75 percent of the

total incremental effect. Normally, within the Bureau of Land Management, chemical or mechanical treatments are not recommended if the objectives in erosion control can be met within 15 years through management alone. BLM made this decision based on the fact that management is more cost effective than other treatments. It is also required to preserve the effectiveness of other treatments once a treatment has been applied. Another factor is the recognition that livestock management plans usually requires two or three cycles to attain their full effects on erosion control. It should also be mentioned that management plans are a requirement before application of any other treatments. This has not always been true, but experience has taught BLM that it must have management first.

**IDENTITY OF AREAS THAT WARRANT FURTHER EVALUATION**

Knowing that the inventory data are collected at an intensity needed to identify erosion conditions throughout the area, it becomes necessary to return to the field when affirmative action is to be taken. The same data parameters are then collected at a greater density for development of action plans. These data will quantify the acres to be treated, the specific treatments and the probable effects.

For example, on a watershed area of 600,000 acres (243,000 hectares), the watershed inventory indicated that additional data are needed on 18 percent of the area to determine the specific areas to be treated in the general magnitude of:

Watershed Tillage	37,000 acres
Mechanical Vegetal Manipulation	20,000 acres
Mechanical Vegetal Manipulation plus Water Control Measures	18,000 acres
Water Control Measures	18,000 acres
Watershed Tillage plus water Water Control Measures	13,000 acres
Chemical Vegetal Manipulation plus Water Control Measures	2,000 acres
Chemical Vegetal Manipulation	2,000 acres

**RANGE CONDITION RATINGS**

Erosion data from the watershed inventory are used along with vegetation data in the determination of range conditions.

Vegetation data are collected on the basis of a single inventory to meet the needs of range (management of cattle, sheep, horses, and burros); watershed (soil erosion, water yield, water quality); wildlife (management of wildlife habitat). These data consist of a multi-level inventory of vegetation designed to identify understory as well as overstory vegetation.

Step-toe transects are made in each major vegetation community. At each data collection point, all vegetation encountered and its relative position in the cover are recorded. In addition, observations are recorded to indicate vegetative species not included at the data points but observed in the process of data collection.

The vegetation data are then rated as desirable, intermediate or least desirable plants for animals grazing the area (cattle, sheep, horses, burros, deer, antelope, etc.).

The vegetation data are then combined with erosion data to rate range condition as good, fair or poor as shown in Figure 4.

**GOOD CONDITION** — Composition is 40 percent-plus of both desirable and intermediate species with at least 20 percent made up of desirable species. Soil surface factor is less than 60.

**FAIR CONDITION** — Composition is 15-30 percent of desirable and intermediate species with 5 percent-plus of desirable species. Soil surface factor is less than 60.

**POOR CONDITION** — Composition is less than 15 percent desirable and intermediate species. Soil surface factor is more than 60.

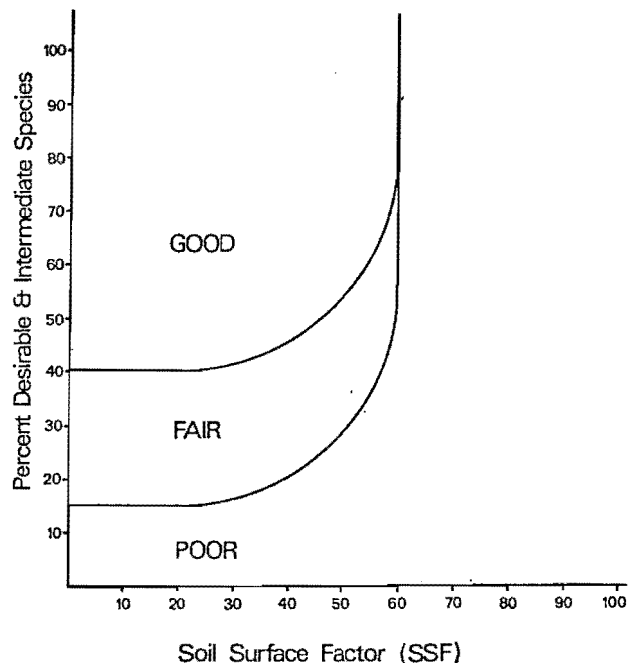


Figure 4.

### ENVIRONMENTAL ANALYSIS REPORTS (EAR)

It is Bureau policy that environmental analysis be conducted for every Bureau action. **Action** as used here includes one or a group of policies, practices or projects. The intensity of the analysis must be determined by the official responsible for the action.

EAR's are prepared in the process of decision-making to determine if a given action should be taken and if an Environmental Impact Statement (EIS) is necessary. Its purpose is to assure that the unquantified environmental value as well as quantified ones are given appropriate consideration in decision-making, along with economic and technical considerations.

For example, actions that may have an effect on erosion are expressed in terms of SSF. Based on similarity of field conditions (i.e., soil, climate, vegetation, use) between the site under consideration and a treated site, a prediction is prepared of erosion changes if the action is taken.

As a general rule, the intensity of analysis is commensurate with the anticipated impact of the decision on the environment.

Following this concept, data from or using procedures for the Bureau's Watershed Inventory are used on all

actions involving manipulation of surface soils. Data obtained from the inventory are used as an expression of present conditions and comparisons are made with treated areas to obtain the anticipated impact.

### JUSTIFICATION STATEMENTS

All funds requested for implementation of land treatment or water control measures must be accompanied with a justification statement. Part of the justification involves an expression of the anticipated affect on erosion; what will the action prevent or enhance. The Watershed Inventory data are a major contributor to these statements. As a basis of comparison, the term stable acres was developed for quantification purposes. The Bureau has accepted a level of erosion activity depicted by a soil surface factor (SSF) of 20 as a point of comparison. This is the point separating what is referred to as STABLE and SLIGHT erosion. For instance, 1 acre having an SSF of 40 is said to be equal to 0.75 acre at an SSF of 20. Therefore, justification statements include the number of stable acres to be obtained by a given action (SSF 20 = 100 percent; SSF 100 = 0 percent stable; or a 1 SSF change = 1.25 percent).

Justification for shifts of funds from one area to another having a better opportunity for enhancement also use this comparison. Within the Bureau, some State Offices have adjusted the distribution of funds between subsidiary offices (Districts) on the basis of general opportunities for improvement.