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Australian Water Resources Council Research Project 68/2

EFFECTS OF LAND MANAGEMENT ON QUANTITY AND QUALITY OF AVAILABLE WATER

A REVIEW

by

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May, 1970

EFFECTS OF LAND MANAGEMENT

ON

QUANTITY AND QUALITY

OF

AVAILABLE WATER.

Australian Water Resources Council
Research Project 68/2

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PREFACE

The project was undertaken at the University of New South Wales in Sydney between March 1969 and March 1970. Funds were provided by the Australian Water Resources Council as part of its water research programme, this being A.W.R.C. Project 68/2 - Effects of Land Management on Quantity and Quality of Available Water. I acknowledge with thanks, the support given by the Council in funding the project, and the services provided for me by the University during the course of the work.

Messrs. John Mills and Guenther Seidel assisted with the collation of bibliographic material and I am grateful to them for the work they carried out. During the project, members of the A.W.R.C. Advisory Panel on the Effects of Rural Land Management on Runoff contributed a great deal in discussions, both individually and as a group, and I gratefully acknowledge this support.

Finally, I offer my thanks to the large number of people throughout Australia, engaged in catchment management activities, who contributed their time for discussion and consultations, and who made it possible for me, in the limited time available, to collate the information contained in this report.

Notwithstanding the assistance received, the opinions, assessments and conclusions contained in this report are those of the writer alone, and not necessarily those of any person or organization mentioned above.

Walter C. Boughton
March 1970.

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CHAPTER 1

DESCRIPTION OF PROJECT

1.1 TERMS OF REFERENCE

This project, which arose out of the recommendations of the Australian Water Resources Council TCSW Sub-Committee on the Effects of Soil Conservation Works on River Discharge, takes into account the broader terms of reference of the Advisory Panel on the Effects of Land Management on Runoff and was designed to direct attention to the most important sources of information from Australia and abroad for use by water authorities in catchment management. The study is also an important prerequisite for future experimental studies or research.

The terms of reference of the project gave definition to some terms, and set out the objectives and scope as follows:

"OBJECTIVES AND SCOPE.

To prepare an annotated bibliography and a critical evaluation of the literature and of current knowledge pertaining to the effects of land use and management on the quantity and quality of available water with a commentary on the applicability and usefulness of various methodological approaches.

The bibliography is to give first emphasis to Australian work but overseas literature is to be searched for information on general principles and methodologies.

Available information on the extent of different forms of present land use and any known hydrological effects are to be reviewed in quantitative terms where possible together with an examination of information on the extent and effects of present trends in intensified land use.

It is expected that these reviews will enable some of the significant gaps in knowledge to be identified especially in relation to quantitative assessments. Where possible suitable approaches for making good these gaps might be proposed.

DEFINITIONS

"Land Use and Management" is to include agricultural, pasture and forestry use, and associated management and conservation practices (minor engineering works would be included where these are part of a particular land use - as in forestry).

Information on "quantity" of water is to be identified in terms of both time and amount where possible.

"Quality" of water refers to sediment, chemical, organic, and micro-biological aspects.

"Available water" refers to both surface and underground water."

1.2 LAYOUT OF THE REPORT

This report is set out in 4 parts:

Part I - A Review of Problems and Available Information

Part II - Methods of Data Collection and Analysis

Part III - Legal, Economic and Educational Aspects

Part IV - Summary and Recommendations.

In Part I, the terms of reference of the project, its objectives and scope are set out. The effects of forestry, agriculture, soil conservation, and some other land uses on quantity and quality of available water are surveyed and the available information on these effects is reviewed and evaluated.

In Part II, the different methods of study which have been used to evaluate the effects of land use on water resources are reviewed and a detailed examination of the effects of forestry, agriculture, conservation, and other land uses on components of the hydrological cycle is made. A review of mathematical catchment models and the possible use of these in future studies of land use are also reported.

In Part III, the legal controls which have been established over land use in water supply catchments in Australia are reviewed and the progress towards economic evaluation of catchment management projects is examined.

In Part IV, the major problems of land use affecting water resources in Australia are briefly summarised and recommendations for supplementing current activities and for filling gaps in existing knowledge are set out.

Each of the 4 parts is set out in chapters. Relevant publications and reports are listed at the end of each chapter and are referenced by number in the text of the chapter.

1.3 I.H.D. WORKING GROUP

When the Coordinating Council of the I.H.D. held its first session in Paris in 1965, there was considerable interest in the effects of land use on water resources. A general resolution was adopted to initiate study of a series of world-wide hydrological problems including "The Influence of Human Activity on Hydrological Regimes". Under the title was added - "main items: influence of agriculture, forest improvement, irrigation, drainage, and watershed management on hydrological regimes".

At the same meeting, in consideration of other special working groups to report on research problems, the Council formed a group to report on "The Influence of Man on the Hydrological Cycle". Again at the same meeting, the Council adopted two further research proposals by F.A.O. on "The Hydrological Consequences of Irrigation and Drainage Projects" and on "The Comparative Hydrology of Forest, Grassland, and Arable Land".

Between the first session and the second session of the Council in April, 1966, it became apparent that if all these proposals were implemented independently, there would be duplication of effort. Therefore, the recommendations were merged into the field of activities of one working group which retained the title "The Influence of Man on the Hydrological Cycle".

The first report of this working group (ref. 29) lists the activities of man that the group reviewed, and these included:-

1. changes in land use involved by forestry, irrigation and other agricultural activities
2. drainage and reclamation
3. erosion control
4. urban and industrial development
5. exploitation of groundwater
6. river control for storage, hydropower, flood abatement, and navigation.

Subsequent to this report, the Chairman of the working group visited a number of countries to enquire of national committees for the I.H.D. whether they had data of sufficient accuracy to detect important changes in the river and/or groundwater regimes, together with an adequate history of land use in the catchment. The Chairman, Dr. H. Pereira, visited Australia in November 1968, and the draft report of the group prepared for presentation to the mid-decade plenary session of the I.H.D. in 1969, includes a good deal of information provided by Australia.

The draft of this report became available early in the present project, and the writer acknowledges with thanks the assistance which was provided by the information collated therein.

1.4 AUSTRALIAN STUDIES

A few bibliographies of hydrology and water resources in Australia have been prepared from time to time. In 1937, the I.A.S.H. bibliography of hydrology in Australia (ref. 13) could list only six entries. However, the bibliography produced in 1962 by the Bureau of Meterology (ref. 7) gives a truer picture of activities with 224 entries. A more comprehensive bibliography is currently being prepared by C.S.I.R.O. to supplement the bibliography of C.S.I.R.O. water research (ref. 11).

Catalogues of research activities in water resources have been prepared by the Australian Water Resources Council (ref. 27) and by the Australia-UNESCO Committee for the I.H.D. (ref. 26). Research effort related to catchment management is listed in these catalogues.

A bibliography specifically on water and land use was prepared in 1953 by the Australian National Library (ref. 6) and in 1960 the Water Research Foundation of Australia financed a study of the efficiency of land treatment measures in the reduction of surface runoff. Results of the study were reported to the Foundation by Vallentine (ref. 30).

Nelson (ref. 28) produced a similar review of the effects of catchment treatment on runoff in 1965, and the general review of information available on water yield by Ayers (ref. 8) in 1962 included aspects related to the effects of land use. Other studies in Australia have been restricted to single aspects of land use rather than broad scope reviews.

1.5 JOURNALS AND ABSTRACTS

Because of the wide scope of activities encompassed by the terms of reference of this project, published reports are spread over a wide range of engineering, agricultural, forestry, conservation and other journals. In addition, much information is available in the proceedings of symposia; research reports and publications which are issued by individual research stations; in higher degree theses from universities; and similar sources. No attempt is made to list all sources of information in the report but special mention is made of the following abstract services which may be of interest to those seeking additional information.

i Abstracts of recent published material on soil and water conservation. United States, Agricultural Research Service, Soil and Water Conservation Research Division (irregular). Washington, D.C.

ii Agricultural and Horticultural Engineering Abstracts. National Institute of Agricultural Engineering on behalf of Commonwealth Agricultural Bureaux, England.

iii Forestry Abstracts. Commonwealth Agricultural Bureaux, England.

iv CSIRO Abstracts. CSIRO Central Library, East Melbourne, Victoria.

v Water Pollution Abstracts. Ministry of Technology, H.M. Stationery Office, London.

vi Water Resources Abstracts. American Water Resources Association, Urbana, Illinois.

vii Selected Water Resources Abstracts. Publ. for U.S. Office of Water Resources Research by Clearinghouse for Federal Scientific and Technical Information, U.S. Dept. Commerce, Springfield, Virginia.

In addition, the following periodical indexes list published material (without abstracts) on aspects of the project:

i Australian Science Index. CSIRO Central Library, East Melbourne, Victoria.

ii The Engineering Index. New York.

iii Hydata. American Water Resources Association, Urbana, Illinois.

iv Applied Science and Technology Index. H.M. Wilson Co., New York.

v Biological and Agricultural Index. H.M. Wilson Co., New York.

vi Bibliography of Agriculture. National Agriculture Library, United States Department of Agriculture.

vii Bibliography of Soil Science, Fertilizers, and General Agronomy. Commonwealth Agricultural Bureaux, England.

The bibliographies and indexes above are periodicals which are issued at various intervals. Many other bibliographies have been prepared, dealing with subjects which form part of the present project. A selection of these is listed in the references at the end of this chapter.

Many detailed reviews with substantial bibliographies relevant to some part of the present project have also been made. These are included in the relevant chapters in this and other parts of the report and are described in context with the other reports and publications which are included.

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CHAPTER 2

EFFECTS OF CLEARING ON AVAILABLE WATER

2.1 INTRODUCTION

One of the major changes that has occurred in Australia in the period of European settlement is that large areas of native bush have been cleared for conversion to pasture or crop. There is little precise knowledge about the effects of this change on the hydrologic cycle, but there is considerable interest in this aspect.

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 usually results. In 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 the salt is accumulated on the surface. Raising of groundwater levels without any problems of salting has been recorded in the Callide Valley of Queensland.

Increased erosion following clearing has occurred in Australia and has been recorded in erosion surveys. The erosion is not evidence in itself of any increase in runoff or in peak rates of discharge, as it seems equally likely to be due to disturbance of the soil during clearing, or the period of exposure while grass is being established, or to subsequent cultivation or overgrazing which follows the clearing.

The clearing of native vegetation for planting of exotic softwood forests, usually radiata pine, has produced problems of turbidity where the clearing has occurred in water supply catchments. There occurs a period of two to three years between clearing of the native vegetation and when the plantation trees grow enough to create an erosion-retarding cover over the ground. An increase in erosion and also an increase in turbidity levels in the water often occurs in this period.

Fire can produce a situation analogous to a severe clearing of vegetation without the establishment of any alternate cover. Fire is treated in detail in a separate section and not considered in this discussion.

In the following sections, a review is made of the relevant studies both in Australia and overseas, which provide some information about the effects of clearing on water resources, and these are set out under the following headings:-

Effects on volume of runoff

Effects on groundwater

Salinity effects

Prediction models for effects on yield

Effects on erosion

Effects on water quality

2.2 EFFECTS ON VOLUME OF RUNOFF

The hydrologic effects of conversion of a catchment cover from trees to grass or vice versa has been of considerable interest to forestors, and there have been many experiments made to monitor the effects produced by clearfelling all trees on a catchment.

Not all relevant studies have been directed to the conversion of trees to grass. Some experiments relate to thinning rather than clearfelling; others to the removal of "phreatophytes", or water loving vegetation, from the edges of watercourses; still others to the reconversion from grass back to trees.

Some general reviews of the literature related to the hydrologic effects of clearing have already been made; by the U.S. Department of Agriculture (ref. 125); by Shachori and Michaeli (ref. 110); by Penman (ref. 86); and a review of Russian literature by Molchanov (ref. 80).

Studies date back at least to the turn of the century and possibly earlier. Hibbert (ref. 52) cites early studies by the Swiss in 1900 on two small catchments in the Emmenthal Mountains. One was almost completely forested the other almost completely pastureland. Measurements of streamflow, precipitation, and climate were made to determine the influence of the differences in cover on the water budget. The results were inconclusive.

The idea of paired catchment experiments (comparing flow from two similar catchments during a period of "calibration" and then treating one while leaving the other as a control) was first used in the Wagon Wheel Gap study in 1911 on two small forested catchments in the mountains of Colorado (see Bates and Henry, ref. 5). After eight years of calibration, one of the catchments was denuded and for seven additional years, streamflow from the denuded area was compared with flow from the control catchment which remained in forest. The study showed an increase in streamflow resulting from the clearing.

Since the Wagon Wheel Gap study, the paired catchment technique has become the most used method for evaluating how the clearing of trees from a catchment affects the amount of runoff. Hibbert (ref. 52) has summarised the results of 39 such studies. The reports summarised in his review include experiments at the Coweeta Hydrologic Laboratory (refs. 42, 51, 59, 60, 61, 65), Fernor Experimental Forest (refs. 99, 100), H.J. Andrews Experimental Forest (ref. 104), San Dimas in Southern California (refs. 35, 78, 106), Sierra Aucha in Arizona (refs. 101, 127), Frazer in Colorado (refs. 46, 75), Wagon Wheel Gap in Colorado (refs. 5, 99), White River in Colorado (ref. 70), Kamabuti in Japan (ref. 76), the Sambret catchment at Kericho in Kenya, East Africa (refs. 89, 90), the Jonkershoek Research Station near Stellenbosch, South Africa (refs. 4, 135, 136), the agricultural research installation at Coshocton, Ohio (ref. 49), Pine Tree Branch and White Hollow catchments in Tennessee (refs. 120, 121), Sage Brook and Sacandaga River in New York (refs. 43, 109), and at Naselle River in Washington State (ref. 74).

After review of the 39 studies included in the above references, Hibbert reported that some general statements could be made about the hydrologic effects of clearing:-

1. Reduction of forest cover increases water yield.
2. Establishment of forest cover on sparsely vegetated land decreases water yield.
3. Response to treatment is highly variable and, for the most part, unpredictable.

Hibbert made it clear that the response to clearing varied so much that no general relationship could be established. However, an increase in runoff due to clearing was evident in almost every study reported.

The most impressive result came from an experiment at the Coweeta Hydrologic Laboratory. Between September, 1939 and January, 1940, all woody vegetation on a 16-hectare (40-acre) catchment was cut and left on the ground; regrowth was allowed. By relating runoff from the catchment to runoff from a control catchment, an increase due to the cutting could be demonstrated and this increase was slowly reduced as the forest grew again. After 23 years, the forest was cut again in November and December, 1962 and the resulting increase in runoff closely paralleled the earlier increase.

Where only part of the catchment is cleared, the resulting increase in runoff appears to be in proportion to the percentage of the area cleared. Hibbert cites results from Coweeta and Fernow to demonstrate this. His results also demonstrate the influence of aspect on the results and the differences which can occur between different localities.

In Australia, Brookes (ref. 23) and Brookes and Turner (ref. 24) report evidence relating water yield of Eucalyptus regnans forest to stand density. The Melbourne and Metropolitan Board of Works have opposed logging of mature trees from the catchments providing Melbourne's water supply for a different reason, i.e. on the grounds that young growing trees will take more water than the mature trees that they replace (see discussion of ref. 79). Brookes (ref. 23) provides some evidence of this but none of the overseas studies of thinning mention this aspect.

Several of the studies cited by Hibbert (ref. 52) were studies of decreases in water yield as previously cleared areas were reforested. These catchments were Bosboukloof and Busiewlei at Jonkershoek; Pine Tree and White Hollow in Tennessee; Cold Springs, Sage, and Shackham in New York; and at Coshocton. The results support the results obtained from studies of forest removal. Other studies reporting similar effects of reforestation are by Ayer (ref. 3), Black (ref. 14), Muller (ref. 82), and Satterlund and Eschner (ref. 108).

The largest scale on which deductions as to the influence of forests on catchment hydrology have been drawn from routine records is on the north-eastern area of European USSR. Pereira (ref. 124) reports that, in addition to very large numbers of detailed analytical experiments on the components of the water balance and more than 2000 highly-instrumented plot studies of runoff relationships from farm-land and forests, Russian research workers have assembled the records of rainfall and riverflow for groups of catchments. These have shown that, under a rather unique set of conditions which occur over a wide area of European Russia, forest cover gives a higher water yield than does farmland. The special conditions are:-

(a) that most of the annual precipitation occurs as snow,

(b) the major runoff events in each year are due to snowmelt,

(c) forest root-range is confined to a shallow layer of about one metre depth.

2.3 EFFECTS OF CLEARING ON GROUNDWATER

The effects of clearing on the hydrologic process can show up as an increase in groundwater recharge rather than an increase in the amount of surface runoff. An example of groundwater rise subsequent to clearing of vegetation in the Callide Valley in Queensland has been documented by Melzer (ref. 77). Most of the Callide area was originally covered by dense forest and dense scrub. From 1924 onwards, a large amount of axe clearing and ringbarking of the scrub and forest followed by burning was carried out.

Between 1953 and 1956, clearing of the vegetation was accelerated by aerial spraying and further accelerated between 1954 and 1961 by the use of heavy equipment. Vegetation maps of the area in 1921, 1945 and 1961 document the progressive clearing and records of groundwater levels in the area show subsequent rises where clearing occurred. Rises of up to 33 feet in groundwater level were recorded.

Melzer (ref. 77) in a detailed study of this phenomenon concluded that the rises in groundwater level were directly attributable to clearing, and that the denser the vegetation prior to clearing the higher the water table rises after clearing. The vegetation maps of the area and the rises in groundwater levels over the last 40 years have been presented in the 1965 Progress Report on Groundwater Investigations of the Callide Valley (ref. 92).

In South Australia, Holmes and others (refs. 53-57) have described the different rates of groundwater recharge between forest and grassland cover in the Gambier Plain. Rainfall and soil moisture storage at two sites in Pinus radiata forest were measured from 1963 to 1965. Results showed no through drainage to recharge groundwater. By comparison, lysimeter studies of the water budget of grassland from 1960 to 1965 showed that an average annual recharge of groundwater of about 3.4 inches could be expected under grassland cover. Roberts (ref. 102) in Western Australia found a similar difference in the annual water use of forest and grassland.

Surface runoff in the area of South Australia studied by Holmes is very small and a current rapid increase in the use of groundwater resources gives importance to differences in the amount of annual recharge. The present proportion of the area covered by pinus radiata forest is small but the amount of available groundwater resource could be affected if this area was significantly increased.

The effects of clearing on groundwater levels have been reported in some European studies. Holstener-Jorgensen (ref. 58) describes results from an investigation carried out in Denmark to show the influence of clearcutting and thinning. On areas that were clearcut, the water table rose considerably during the growing season. On areas that were thinned, the rise was not quite as high and suggested a correlation between the amount of cutting and the subsequent rise in groundwater level. The water table was raised about two metres after clearcutting and by about one metre after thinning.

As a new plantation became established on the clear-cut area, the water table was lowered during the growing season. The same result was obtained as the thinned stand closed again. Some conclusions from this study were that the root depth of the tree species largely determines the opportunity for water use that the tree will command, and that evapotranspiration loss is related to stand density.

Heikurainen (ref. 50) reports similar results from studies in Finland. Cutting was again shown to cause significant rises in groundwater level, and the amount of rise was proportional to the amount of thinning carried out.

However, Pereira (ref. 124) cites an example of the reverse effect, i.e. a rise in groundwater level in the USSR as a result of the presence of trees. The particular conditions are that most precipitation occurs as snow on frozen soils. Infiltration rates are important during the period of spring snowmelt. Large-scale plantings of broad shelter-belts of mixed hardwood and conifer forests, 50-100 metres wide, have been made over the past century, while intensive planting of narrow shelter-belts, only 10-15 metres wide, and 200-300 metres apart, is continuing today. Observations on groundwater wells within and outside the older forest shelter-belts have continued since 1892. They show a clearly defined rise in the level of the water table under each belt of forest.

Urie (ref. 129) draws attention to the need to allow for unmeasured groundwater seepage out of a catchment when accounting for fluctuations in groundwater levels by water balance techniques. Lewis and Burgy (ref. 69) report on a study in California in which change in groundwater storage is incorporated into the water budget of an experimental watershed.

2.4 EFFECTS OF CLEARING ON SALINITY

The studies cited in the previous section show that rises in groundwater level can occur when deeprooted trees are replaced by shallow rooting grasses. When the groundwater is saline, as occurs in many areas of Australia, the resulting effects due to the salt can be far more evident than any changes in the volume of groundwater or in the volume of surface runoff.

This has been most evident in Western Australia where the problems of salinity following clearing have been recognised since the beginning of the century. Almost 50 years ago, Wood (ref. 139) reported on the increase of salt in soil and streamflow following clearing of the native vegetation. His concern was in connection with railway water supplies as the increasing salinity made water from many dams unsuitable for locomotive boilers.

The development of saline areas in creeks and gullies became more widespread as clearing developed in the 15" - 25" rainfall area. Smith (ref. 14) gives an excellent review of the problem and Pennefather (refs. 87, 88) gives another. Pennefather in 1951 estimated that 100,000 acres of previously cropped valley soils were affected. A survey carried out by Burvill in 1955 (ref. 26) indicated that 181,000 acres were then affected, and another survey in 1962 (ref. 70) showed 300,000 acres affected. Current estimates of the area affected are in excess of 400,000 acres.

Matheson (ref. 141) describes the occurrence of the problem in South Australia and estimates that 30,000 acres are affected on the Eyre Peninsula. Cope (ref. 29) has surveyed the incidence of catchment salting in non-irrigated areas in Victoria, and estimated the area affected as more than 10,000 acres consisting mainly of better class lands in valleys and flats. Cope gives a good review of the earlier literature and lists evidence in support of rainfall as the source of salt in the catchment systems. He attributes the increase in salt affected areas to upset of the hydrologic balance following clearing.

The problem has been described further in more recent reports by Downes (refs. 38, 39). Rowan and Downes (ref. 105) also describe "seepage salting" in a study of the land systems in North-western Victoria. They report:-

> "Seepage salting has undoubtedly developed as a result of a change in the hydrological pattern which followed clearing of the native vegetation.

> The mallee and savannah mallee of the dunes and the mallee of the lower sites had a high potential transpiration rate so that there was relatively little seepage from the dunes and any moisture which did accumulate in the lower sites was quickly transpired, thus minimizing evaporation. After clearing, the land was bared by fallowing and by erosion, and shallow-rooted species incapable of tapping moisture at depth were frequently grown. Thus transpiration decreased, resulting in increased seepage from the dunes and in waterlogging on the flats. The fact that seepage salting does not occur to the north of approximately the 12-inch isohyet indicates that this line marks the dry limit to significant seepage."

Bettenay, Blackmore and Hingston (refs. 9, 10) investigated the reasons for the increase in salinity of soils in the Belka Valley which lies in the wheat belt of Western Australia. In the area studied, the major reservoir of salt in the catchment system is in a confined aquifer system and has accumulated through atmospheric accession. Salinity of overlying soils was found to occur where capillary contact with the surface occurred in the valley bottoms. Salt accumulated at the surface as the water evaporated.

Collis-George and Evans (ref. 28) describe a similar situation in an alluvial plain of the Hawkesbury River in New South Wales. These authors show that depth to the water table is critical in determining salt accumulation in the surface soil when the groundwater is saline. In this latter example, fluctuations in the balance of rainfall and evaporation from year to year is the reason for changes in the depth to the water table and subsequent changes in the amount of salinization of the surface soil.

Observations in Western Australia show that the first appearance of surface salting may occur within a few years after clearing and the salt accumulation reaches a maximum after 10 to 20 years (ref. 137). The Department of Public Works of Western Australia, which is responsible for the water supply to Perth and the surrounding district, has commented (discussion of ref. 79) that control of activities requiring clearing of vegetation from catchment areas is of prime concern in the management of the water supply because of increases in salinity which follows clearing. A branch of the Collie River feeding Wellington Dam has 10% of its catchment cleared but the salinity is about three times as great as that from two other feeder rivers which drain from uncleared land. In addition, salinities in the Mundaring storage were noted to increase when trees on part of the catchment were killed by ringbarking in an attempt to increase runoff.

There are different variations of the problem of increased salinity following clearing and different authors have described variants of the general theme.

Pennefather (ref. 87) describes two types of salinity, i.e. salinity due to seepage and broad valley salinity. According to Pennefather salinity due to seepage occurs where impermeable sub-surface clays come very close to the ground surface downslope from quite permeable deep soils. This type of salinity develops with unconfined aquifer systems, particularly on deep sands in low rainfall areas of Western Australia and on the ironstone gravel soils of the higher rainfall areas.

Broad valley salinity is described as having two variations - one which is associated with confined leaky aquifer systems in the valley bottoms where the medium textured soils have a depth overlying the leaky aquiclude of less than six or seven feet. The other variation is in situations where there could be a confined aquifer close to the soil surface, but where the dominant cause is from a perched water table developing in the sands overlying the aquiclude of the valley floor.

Smith (ref. 113), in a description of the problem in Western Australia, gives different names for what appear to be essentially the same types. He describes valley water logging as occurring where the land is underlain by shallow water tables, usually six or seven feet from the surface. This is the most extensive form of the problem and occurs in broad flat valleys of low gradient. The other form is hillside seepage in which salt appears on hill slopes where water seeps to the surface. These seepages are common in higher rainfall areas.

Smith attributes both forms to clearing as deep rooted native vegetation is replaced by shallower rooting cover. The amount of rainfall utilised where it falls is reduced and groundwater recharge is increased. Groundwaters are saline in the problem areas and salt accumulates where the water table comes close enough to the surface to evaporate, either in seepage areas on hillsides or in the valley bottoms.

Cope (ref. 29) also states that catchment salting is found in two main topographic positions, on the sides of slopes, and in flats at the base of slopes. However, he separates the salting of flats into hardpan salting, in which the soils are wet in winter but dry out quickly in summer leaving the surface baked hard, and wetpan salting in which the soil does not dry out sufficiently to bring about the death of vegetation by water shortage in the presence of salt.

Rowan and Downes (ref. 105) also describe seepage salting but do not distinguish between hillside and valley floor forms as do the other authors. Rowan and Downes, together with Bettenay et al, and Smith, also describe "dry land salting" in which salting occurs following clearing but in the absence of a water table. This latter form occurs on heavy textured virgin soils under low rainfall conditions where there is no excess water for leaching of salts brought in by rain and salt accumulates in the soil profile. The mechanism of how this form of salting is affected by clearing is not clear.

2.5 PREDICTION MODELS FOR EFFECTS ON YIELD

Few attempts have been made to incorporate the differences between forested and grassed catchments into a calculation model for estimating differences in catchment yield. Mathematical catchment models currently used for relating runoff to rainfall have not been used for this purpose, probably because the accuracy of relationship which is obtainable at present is inadequate to show up the small differences produced by clearing.

The procedure developed by the United States Soil Conservation Service (ref. 126) for estimating runoff from rainfall incorporates adjustment factors for both pasture areas and forested areas. By using each of these factors in turn, it would be possible to estimate the difference in yield due to clearing if the method was accurate. However, use of the method in Australia to date has not produced results of sufficient accuracy to be encouraging.

For example, the U.S. S.C.S. method was used to analyse 18 station years of runoff data from six farm dams and one research catchment in Queensland (ref. 93). It was found that the method consistently underestimated the occurrence of runoff, correctly predicting only 57 occasions out of 179, and in estimating runoff magnitude, the error in nearly half of the derived runoffs was about 80% or greater It is obvious that the errors involved in use of this technique are of a greater order of magnitude than the differences produced by clearing.

The accuracy obtained from mathematical catchment models is much better than the accuracy obtained from the U.S. Soil Conservation Service method. Boughton (refs. 16,17,18,19) has published results from a catchment model using daily rainfall and runoff data from six catchments in Australia and five catchments in New Zealand. The results obtained have a substantially higher accuracy than those from the Queensland study cited above. Catchment models offer more hope of improvement to the stage where they can be used to delineate the effects of clearing.

In Part II of this report, dealing with experimental methods and methods of analysis, a review is made of the catchment models for which published information is available (see also refs. 20, 21, 22). At present, no catchment models have been prepared or used for the purpose of estimating the effects of clearing on runoff. In December, 1968, an IASH - UNESCO symposium on the Use of Analogue and Digital Computers in Hydrology was held at Tucson, Arizona. Many of the 78 papers presented dealt with current developments in mathematical catchment models but only one mentioned any use of these models for evaluating change in land use, and this was concerned with the effects of urban development.

From the evidence available in the references cited in this chapter, it seems clear that the principal reason for the effect on water yields caused by clearing is the difference in root depths between trees and grass. Where the climate is such that there is opportunity for the soil profile to be depleted of moisture at frequent intervals, deep rooting trees can extract more soil moisture than shallow rooting grasses and so create a greater deficit to be replenished by the next storm. The lesser deficit under grass results in greater runoff or groundwater recharge from the storm.

In Part II of the report, a review is made of the effects of land use on components of the hydrological cycle. There is little evidence that the differences in interception capacity, infiltration, depression storage, or potential evapotranspiration rate between trees and grass can systematically account for the observed differences in runoff and groundwater recharge. All evidence points to the differences in soil moisture available to the plants, caused by differences in root depth, as the significant factor in producing the increase in available water following conversion from trees to grass.

One other factor of equal magnitude in affecting runoff is the effects of slope and aspect of the ground surface on the amount of radiation received. Sloping ground which faces the equator receives more radiant energy and loses more water by evapotranspiration than slopes which face the pole. This factor influences grassed catchments as well as tree covered catchments and is not a factor in causing any hydrological changes following clearing; however, the influence of slope and aspect must be considered when making comparisons between catchments to assess the differences between grass covered and tree covered areas.

2.6 EFFECTS OF CLEARING ON EROSION

Erosion can be increased when forest or scrub is cleared. The soil is often disturbed by clearing, and can be exposed if there is an interval between clearing and the growth of grass or crop over the area. Salinity produced by clearing as described earlier can play a part by killing vegetation and further exposing the soil to erosion.

An erosion survey of the Eastern and Central Divisions of New South Wales was made during the years 1941-1943. The results, originally reported by Kaleski in 1945 were republished in 1963 (ref. 63). A re-survey of the same areas was made in 1967 and comparison of the two surveys was reported by Stewart (ref. 117). In the 25 years between the surveys, there had been an increase of almost 3000 sq. miles in the total area of moderate gully erosion. Stewart reports:-

> "The state-wide increase in this class of erosion is due almost entirely to increased clearing and cultivation, about 70% of the increase being in the wheat growing area of the slopes and plains."

The total area described as "severe and extensive gully erosion" decreased from 882 to 826 sq. miles but decreases in some districts were balanced by increases in others. The increases in this class of erosion were again attributed to clearing and cultivation.

One major phenomenon in New South Wales that could be attributed to the effects of clearing is the "raft" which now forms a permanent blockage of the Gwydir River immediately downstream from Moree. The blockage is formed of river-borne dead timber and silt in which green timber now grows. The length of the filled-in river channel increases with every major flood. The blockage is thought to have been initiated about the end of the last century, was over three miles long in 1921, and was reported to be about nine miles long in 1962. It seems likely that the "raft" could be one of the more lasting effects produced by clearing of land in New South Wales.

Downes (ref. 38) reports increases in erosion as a result of clearing of land in Victoria. In the areas where clearing has raised saline groundwater levels to produce problems of salinity as previously described, the increases in surface runoff and the increases in groundwater levels have also produced increases in erosion. Downes reports:-

> "Less water is now being used in the catchment than under natural conditions and the increasing amount of runoff has initiated a new cycle of erosion in the watercourses. Furthermore, unused water in the tablelands and the upper valley sides is escaping to the deep subsoils, and the increased seepage is causing excessive wetness in the valley sides. This has caused an increase in the incidence and extent of landslips and earthflows."

There appears to be several different aspects of the relationship between clearing and increased erosion.

i. Removal of the vegetative cover and disturbance of soil during clearing can increase the susceptibility of the soil to erosion.

ii. Poor management of grazing and cultivation following clearing are likely to increase erosion.

iii. Where increased salinity of the soil follows clearing, the killing of vegetation by the salt further increases the susceptibility of the soil to erosion.

iv. Raised water tables can cause landslips and earthflows in the valley sides.

v. Increased surface runoff may cause increased erosion.

One particular area of erosion is the high mountain country of the Australian Alps which is important in providing 25% of the annual yield of the Murray River from 1% of its catchment area. Runoff and erosion in these areas have been studied in some detail.

In 1935, Craft (ref. 32) attributed the main gully erosion of this area primarily to a recent revival of cutting forces due to the advent of increased flood flows caused by rainfall intensity change. He maintains that, though settlement may have accelerated erosion in some cases, the position was already unstable and recent cutting is geologic rather than due to runoff increase or other effects of settlement.

However, Morland (ref. 81) states that the soil of the catchment was essentially stable prior to white settlement and that the erosion now evident results from settlement. He states:-

> "By conversion of large areas of forest land for grazing and farming, by destruction of protective soil cover by fire, and by the breaking down of watercourse stability, settlement has upset the natural balance and has accelerated erosion."

The erosion appears to be as much a result of overgrazing as of clearing. Costin (refs. 30, 31) reports results from plot studies which show that percentage ground cover is of more importance than type of cover, and that a dense herbaceous cover was more suitable for control of surface runoff and soil loss than woody cover.

2.7 EFFECTS OF CLEARING ON WATER QUALITY

Clearing operations produce two effects on water quality in Australia. In Western Australia, problems of salinity following clearing have occurred in the catchments providing Perth's water supply. This aspect is discussed in Section 2.4. The other effect is that of increasing turbidity in water supplies following clearing in catchments on the eastern side of the continent.

Problems of turbidity caused by clearing to plant softwoods have occurred recently in the Shoalhaven River catchment in New South Wales; increased turbidity due to forest roads has occurred in the Cotter River catchment supplying Canberra's water; and careless logging operations have caused problems with the Kilmore water supply in Victoria. The turbidity problems with Canberra's water supply resulted in an enquiry in 1966 (ref. 144) and a report by the Commonwealth Department of Works (ref. 145). Other studies of the Cotter catchment have been made at the Australian National University (ref. 146, 147), and by the Institute of Foresters of Australia (ref. 148).

Experiments to study the effects of clearing and forest management on turbidity are now current in Queensland and Victoria, and are being planned for New South Wales. A more detailed discussion of the problem is given in Chapter 4 - Forests.

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CHAPTER 3

EFFECTS OF AGRICULTURAL AND SOIL CONSERVATION PRACTICES

3.1 INTRODUCTION

Soil conservation in Australia is generally associated with works and practices to reduce the rates of soil erosion to acceptable levels, and conservation programmes have mostly been aimed at farm-by-farm improvement. In recent years, two significant changes have occurred. Conservation programmes have been enlarged from the farm as a unit to the treatment of whole catchments; and the philosophy of soil conservation has progressed from the prevention of erosion to total programmes of land use aimed at achieving maximum sustained yield from the land.

In the broadest sense, conservation is now regarded as including afforestation (particularly protection forests), agronomic practices such as management of fertility, as well as structural measures such as banks, gully control structures, flood detention dams, and so on.

The Sub-Committee on Effects of Soil Conservation Works on River Discharge (ref. 1), appointed by the Australian Water Resources Council, classified soil conservation works as:-

(a) mechanical - diversion banks, farm dams, etc.

(b) vegetative - treatment of localised areas with vegetation for erosion control, e.g. better stabilization, grassed waterways, etc.

(c) agronomic - pasture improvement on a paddock or on a catchment scale.

(d) land-use - replacement of one type of land use by another - e.g. afforestation of an eroded grassland catchment, or replacement of poor quality eucalypt forest by improved pasture.

The Sub-Committee also drew attention to the 150 separate types of activity listed by the Soil Conservation Service of the U.S. Department of Agriculture as evidence of the variety of works in modern conservation programmes.

In the present study, the influence of forests is treated in detail in a separate chapter, and discussion of the effects of afforestation is not repeated here. Agricultural practices, however, are closely related to conservation activities and it is expedient to consider both of these topics together. The activities which are considered in this chapter are grouped into the following sections for brevity:

1. Mechanical - banks and terraces, contour cultivation.
2. Agronomic - crop rotations, fertility, mulching, change of cover type.
3. Grazing - grazing density, sheep vs. cattle.

Conservation and agricultural activities affect soil loss and water quality in addition to the rates and amounts of runoff, but, for clarity, the effects on water yield and rates of flow are considered first. The effects on water quality are dealt with in a separate section.

3.2 EFFECTS ON QUANTITY AND RATES OF RUNOFF

The methods of study used to determine the effects of conservation and agricultural practices on runoff vary considerably. Some studies are conducted on small plots using artificial rainfall; others on small catchments of a few acres in area; and others on catchments of a few hundred square miles in area.

There is considerable controversy and much doubt about the validity of extrapolation of results from plots and very small catchments to large drainage basins. In order to avoid any confusion, a review is first made of the effects which have been observed on plots and small catchments, and then studies on large areas are dealt with separately. Finally, some consideration is given to the problem of extrapolation from small to large areas.

3.2.1 EFFECTS OF MECHANICAL WORKS

The most commonly used mechanical works in conservation programmes, as evidenced by descriptions in the available literature, are dams (both storage and detention), graded and contour banks and terraces, and the effects of contour cultivation which produces small but widespread surface storage of water.

Dams have the most influence on volume and rates of runoff, but, as the influence of these works is dealt with in detail in another chapter, the review is not repeated here.

The construction of banks or terraces is common in soil conservation practice, both in Australia and other countries. Banks may be graded to divert the direction of surface runoff, usually across the general slope of the land, or they may be level to hold water in storage for subsequent infiltration. Graded banks usually divert runoff to a prepared waterway which can carry peak flows to an outlet area without erosion. They act to slow down the rate of runoff rather than store water as in absorption banks. Ogrosky and Mockus (ref. 2) give a description of the types and dimensions of terraces used by the U.S. Soil Conservation Service.

The evidence available for evaluating the effects of terraces on runoff is not good. Some studies have many conservation measures incorporated into a single experiment, and it is difficult to isolate the effects of individual measures. In the few other studies, the experimental methods used are often suspect, e.g. very short calibration periods or no control used. While most studies directed to flood flows indicate a reduction in rate of runoff from small areas due to terraces, few studies demonstrate any reduction in catchment yield, and the available evidence is conflicting.

The difficulties of evaluating effects on runoff are illustrated by the confused results obtained by Sharp, Owen and Gibbs (ref. 5) on a study of four small catchments at Hastings, Nebraska. An experimental catchment, W-5 of 411 acres, was initially paired with one control catchment, W-3 of 481 acres, and this pair was operated from 1938 to 1947 as a calibration period. Conservation treatment of W-5 was undertaken in the period 1947-1950, the treatment including terracing, contour cultivation, increased areas in pasture, and improved rotations.

When the data was analysed, a double mass plotting showed that a change in the runoff relations between the two catchments occurred about 1945, two years before the treatment was started. Runoff of W-5 went down with respect to W-3.

Two other untreated catchments, W-8 of 2086 acres and W-11 of 3490 acres, were then compared with both W-3 and W-5. These additional checks showed that there was no change in the runoff pattern of the treated catchment W-5 compared with W-8 and W-11. However, the untreated control catchment W-3 showed a distinct change in runoff pattern compared with each of the other catchments.

Additional comparisons were then made with smaller catchments about 3.5 acres in area, and a change in flow regime of W-3 was again evident. There was nothing that the change could be attributed to. There was no evidence of any change in runoff from W-5 due to the conservation treatment.

Sharp, Owen and Gibbs also studied 20 years of data from small (three acre) catchments at Red Plains Conservation Experiment Station at Guthrie, Oklahoma. Studies on one catchment indicated that when an unterraced cultivated area is converted to grassland, a 45% decrease in runoff would result; but studies on another catchment indicated that when a terraced cultivated area is converted to grassland, a 40% increase in runoff would result.

A group of 12 catchments, ranging in size from 3 to 300 acres at Blacklands Experimental Watershed, Riesel, Texas, was also studied by the same authors. There were a number of untreated control catchments and different treatments or combinations of treatments on the experimental catchments. The data had a weakness in that the catchments were calibrated during a period of rainfall which was above the average of 33 inches per annum, and the results after conservation treatment were obtained in a period of below average rainfall.

The results showed that a package conservation treatment consisting of terraces and contour banks, increasing the area in grass, and an improved crop rotation, would reduce the annual runoff by 0.5 inch or about 30% of the average runoff. Analyses of individual treatments showed that terraces and banks alone would result in a slight <u>increase</u> in runoff of 0.1 inch per year.

Baird (ref. 6) also reports on experiments at Blacklands Experimental Watershed and confirms that no distinct effect on water yields could be found, although some reductions in peak rates of flow were attributed to a combination of improved crop rotation and terracing.

Sharp, Gibbs and Owen, together with Harris (ref. 9) used regression analysis to test the significance of several factors on annual yield from the Delaware River Basin of Kansas, and found that miles of terraces per square mile of catchment area was not significant.

Nelson (ref. 8) cites a review by Stallings (ref. 7) of the effects of terracing on crop yields, runoff, and soil loss in the U.S.A. Experiments from seven states of the U.S., including 20 cases, showed a change in average annual runoff due to terracing ranging from a 100% decrease to an increase of runoff from the terraced area amounting to 38%. In five cases out of 20, the effect of terracing was to increase runoff.

Hobbs (ref. 10) describes experiments on three small (3-8 acres) catchments in corn-grain-hay rotation at Maryland Agricultural Experiment Station, the study period being 1939-1945. Results indicated an increase in magnitude of runoff peaks where tillage considerably off the contour was practiced, compared with contour strip cropping. Where diversion terraces were used in conjunction with the rotation contour cropping, a decrease in the number and magnitude of peak flows was indicated. This was attributed to the channel storage in the terraces which spreads out and reduces the peaks and delays the runoff.

In general, there is little evidence that contour banks or terraces have any significant effect in reducing the total yield of a catchment. There is some evidence to show that runoff peaks from small areas are reduced by banks but the available evidence is insufficient to make generalised statements about the amount of reduction to be expected from floods of different magnitude on catchments of various sizes.

3.2.2 AGRONOMIC PRACTICES

There are many agronomic practices in conservation programmes, and different combinations of practices are involved in different treatments. Evidence related to isolated practices is difficult to find, as most results are from a combination of practices together. The major comparisons between conservation practices and prevailing practice for which there is some evidence of influence on the hydrologic cycle are:

cropped areas	vs.	grasslands and/or woodlands
improved rotations	vs.	poor or single cropping
heavy fertilizer application	vs.	light applications
improved pasture	vs.	native pasture

Logan (ref. 19) describes experiments on 1/30th acre plots 182 feet in length at Wellington, New South Wales, to examine the differences in runoff and soil loss among different land treatments. The land treatments studied were:

wheat - fallow rotation

wheat - oats - fallow rotation

lucerne

land retired from cultivation

Records for the period 1948-49 to 1956-57 showed that more runoff came from the two cropping treatments than from the two grazing treatments. Totals of runoff fro the individual treatments were:-

Wheat - fallow rotation	-	8.24 ins.
Wheat - oats - fallow rotation	-	8.85 "
Lucerne	-	2.66 "
Retired from cultivation	-	3.83 "

Logan summarised the expected frequencies of runoff from the various treatments in the form of a series of graphs. Jones (ref. 23) reported the results of a similar analysis of runoff from small plots at the Wagga research station. Lamy (ref, 24) reports some results of runoff and soil loss from summer storms at the Wagga station in the summer of 1947-1948.

Dunin and Downes (refs. 14, 15) report the results of experiments to test the effect of replacing poor native pasture with subterranean clover and wimmera ryegrass in controlling surface runoff from four-acre catchments near Bacchus Marsh, Victoria. The four catchments were in two pairs, one pair with north-west aspect and the other with south-east aspect. After calibration from 1955 to 1959, one catchment in each pair was converted to improved pasture, and data from 1960 to 1963 were used to assess the effects.

Comparisons were made using annual yield coefficients, storm yield coefficients, and runoff rate coefficient. The results were variable. A significant reduction in annual yield coefficient was found on the treated catchment with north-west aspect but not on that with south-east aspect. Storm yield coefficients were affected in spring and winter but not in summer storms. Runoff rate coefficients were not reduced by the changed land use.

Hickok, Mayer and Kohnke (ref. 26) describe results from a statistically designed experiment on 12 small (2-3½ acres) catchments at Lafayette, Indiana from 1942 to 1947. The experimental design was for:

3 crops x 2 treatments x 2 replications = 12 catchments

Crop rotation was corn- soybean - wheat - meadow giving comparison of corn, wheat and meadow. The prevailing practice which was one treatment included straight row seeding, moderate fertilizer to corn and wheat, mixed red clover and timothy seeding for the meadow, and partial removal of crop residue. The conservation treatment included contour seeding, heavy application of commercial fertilizer to corn and wheat, and manure ploughed under for corn, the addition of lucerne and alsike to the meadow seeding and return of all residue.

Analysis of peak rates of runoff showed that all runoff rates in excess of two inches per hour from rotation crops occurred when the catchments were in corn; and of 17 occurrences of these high runoff rates from catchments in corn, 13 were from prevailing practice and only four from the areas under conservation treatment.

The annual and also the crop-period volumes of runoff from catchments in corn and wheat were similar and about twice as much as those from catchments in meadow under the prevailing farming system. The conservation treatment reduced runoff from corn and wheat to approximately that from the meadow areas. One of the most significant results from the study was that conservation treatment had little effect on runoff totals from the meadow catchments.

Sharp, Owen and Gibbs (ref. 5), in a comprehensive review of available data on land-use effects in the U.S.A., also analysed records from these catchments for the period 1940-55, and they present double mass curve comparisons of runoff between catchments as well as results from statistical analysis. These authors comment:

> "These data at Lafayette are among the few found where there was sufficient replication to permit statistical comparisons (analysis of variance)."

These authors cautioned against extrapolating results from the small catchments to larger areas. They also analysed runoff records from 15 small (3-4 acres) catchments at Hastings, Nebraska to determine the effects of different crops on surface runoff. A crop rotation of corn, oats, and wheat was used on all catchments. In each year, five catchments were in each crop. Corn showed the least surface runoff and wheat showed the most, but the differences were not statistically significant. Runoff records from nine small (2-9 acres) catchments at the Wheatland Conservation Experiment Station at Cherokee, Oklahoma, showed that conversion from continuous wheat cropping to grassland appeared to decrease runoff but no definite conclusions could be drawn.

Harrold (ref. 22) reports another comparison between poor prevailing practices and improved conservation treatments. A 4-year rotation of corn-wheat-meadow-meadow was used on both treatments, the main differences in the comparison being heavy vs. light applications of fertilizer, and contour vs. off-contour cultivation.

Records from four pairs of catchments, each about three acres, were analysed by double mass curve plotting. The results did not show any effect on runoff by the improved agronomic practices.

Neal and Butler (ref. 27) report comparisons of run-off and soil loss from untreated; annual cover (vegetable crops); and annual manure treatment, on small plots at the Marlboro Soil Conservation Experiment Station in New Jersey. There were about 70' slope lengths x 14' wide of untreated, annual cover crop, and manure treatment; and one 210' slope length x 14' wide on an untreated area.

The increased slope length did not have any effect on rate of runoff but soil organic matter additions, either from cover crop or manure, were effective in reducing runoff rates during the growing season. The authors report that the relative effectiveness of the organic matter treatments decreased as rainfall intensity increased.

Smith (ref. 20) describes crop residue mulching as one of the more promising practices at present in soil conservation in the U.S.A. In 1942, Borst and Woodburn (ref. 21) tested mulches held on screens one inch above the surface of 6' x 29' plots on 12% slope with artificial rain applied from a type E simulator. This study showed that it was the surface crust formed by rainfall impact in the absence of mulches that caused increased runoff. Holding the mulch on screens did not produce more runoff or soil loss than when the mulch was on the surface of the ground. The effect of rain-dispersed soil particles in clogging pore spaces and sealing the soil surface has been described by Lowdermilk (ref. 28), Hendrickson (ref. 29) and Duley (ref. 30).

Dreibelbis and Amerman (ref. 32) studied the effects of land use, soil type, and agronomic practices on the water budget of lysimeters and small catchments at Coshocton, Ohio. Analyses of the data showed that, on similar soils, areas with a shallow rooted poverty grass had greater percolation and runoff and less evapotranspiration loss than areas with a cover crop of deep rooted birdsfoot trefoil. During each of five growing seasons, deep rooted vegetation extracted an average of 3.5 inches more water per year than the shallow rooted vegetation.

Blank and Beer (ref. 41) used multiple linear regression to determine the factors affecting water yield on 14 catchments with an average of ten years of record on each. They present prediction equations for estimating yield from climatological, agricultural and antecedent moisture parameters. Wischmeier (ref. 36) has assembled data from a wide range of locations in order to prepare a runoff prediction equation, similar to his universal soil loss equation, based on statistical analyses.

While statistical methods are often useful in identifying which factors are important, there seems more to be gained from analyses based on deterministic models of the physical processes involved, rather than from stochastic analysis of runoff data. With this point in mind, an attempt has been made to delineate the physical principles involved when conservation treatments and practices affect runoff.

From the studies mentioned above and the others which have been omitted for brevity (refs. 37 to 56 inclusive) a pattern of cause and effect has emerged. About 90% of the studies reviewed record effects on runoff which could be explained in terms of control on evapotranspiration loss, rather than on interception, infiltration, surface depression storage, or other components of the hydrological cycle. This conclusion arose after the detailed review of the components of the hydrological cycle which is made in Part II.

Two effects seem to dominate. Where there is a change in vegetation types that results in a change in root depths, there is usually less runoff or groundwater recharge from the deeper rooted vegetation than from the shallower rooted. The opportunity for more water use with deeper rooted plants has been most clearly demonstrated in comparisons between trees and grass as described in the chapter on the effects of clearing.

The other influence on evapotranspiration loss that affects runoff is where practices such as fallow are used to stop or greatly restrict water use by plants. Where there are no mulches or litter to shield against raindrop impact, surface sealing may be significant in reducing water intake and so increasing runoff. However, in such cases, there would be little vegetation to use water by transpiration, and the effect of no transpiration loss seems to be of much greater importance in the overall water balance.

3.2.3 GRAZING

The most significant hydrological problem associated with grazing, not only in Australia but throughout the world, is that of increased erosion when the protecting plant cover is removed by overgrazing. In arid and semi-arid areas, rainfall is usually highly variable, and stock management becomes difficult. Frequently, stock numbers are allowed to increase in a succession of good years, and the usual result is severe overgrazing when a drought year occurs.

Two surveys of literature dealing with the hydrological influences of grazing have been made. Reppert and Green (ref. 63) prepared an annotated bibliography of publications from the San Joaquin Experiment Range, related to range management and cattle grazing. This lists 135 relevant papers and reports. Lull (ref. 70) has reviewed available literature related to the compaction of soil on forest and range lands by logging, grazing and other agencies.

In New Zealand, Hughes, McClatchy and Hayward (ref.4) made a detailed investigation of the effects of replacing sheep by cattle in the hill and high country of the South Island. Differences in the methods of prehension (seizing and conveying food to the mouth), differences in hoof pressures, and preferences for locality of grazing were examined to see if one type of beast was likely to produce greater runoff or erosion than another. The authors concluded that soil erosion was more directly influenced by numbers of livestock than by their class, and that there was enough evidence to reject any hypothesis that cattle reduced the rates of runoff compared with sheep.

Costin (ref. 62) has reported on the problems of erosion resulting from overgrazing in the Australian Alps. Surveys of the extent of erosion damage (refs. 76,77) and of vegetation deterioration (ref.62) have been made. The areas concerned form the catchments for the $800,000,000 Snowy Mountains Hydro-Electric Scheme, and grazing of areas above 4500 feet was prohibited in 1958 to protect the condition of these high runoff areas. Bryant (ref. 78) describes the trends in vegetation regrowth and re-establishment of the ground cover following the exclusion of stock.

Toebes, Scarf and Yates (ref. 79) report on the effects of improving small catchments subject to hard grazing. The land improvement was by oversowing and topdressing. The pastures were kept at or below an average height of $1\frac{1}{2}$ inches by the hard grazing. The authors report some decrease in annual runoff, an increase in surface detention, a reduction in the number of days on which flow occurred, and decreases in peak rates of runoff, due to the improved practice.

Generally, there have been fewer studies of the effects of grazing on runoff than of other aspects of land use such as clearing; and many of the studies have been made on small, fractional-acre plots. However, within these limitations, some general observations can be made.

Most evidence suggests that runoff increases when the level of grazing is increased (refs. 57-59, 64-69). It seems obvious that if heavy grazing reduced the ability of the plant cover to transpire, there would be less water used by the plants, higher soil moisture levels, and more runoff. But the available evidence consists only of simple observations of amount of runoff and there are no detailed water balance studies to indicate cause and effect relationships.

One common hypothesis has been that increased grazing is associated with increased compaction of the surface soil with consequent reduction in infiltration rates. Many of the available reports (refs. 71-75) mention such effects. However, when the surface vegetation has been removed to the extent that compaction by treading of the surface soil is possible, then the increased soil moisture due to reduction in transpiration loss can also be a significant factor in reducing infiltration rates. The hydrological changes produced by change in grazing pressure are complex and the available evidence is insufficient to delineate causes and effects with any certainty.

A great deal of attention has been given to the problem of how much plant cover is required in order to protect against erosion. In the U.S.A., a very simple rule of "take-half-and-leave-half" is often quoted as an index of how much grazing a pasture can tolerate before accelerated erosion commences. But usually, more specific figures are suggested, e.g. Costin et al (ref. 105) found that effective erosion control is provided in the high mountain catchments of the Australian Alps by continuous herbaceous cover at a density of about four tons/acre dry weight and about 11 tons/acre when the cover is sclerophyllous. Condon, Newman and Cunningham (ref. 80) set out a method for determining the grazing capacity of arid lands in Central Australia based on the application of rating scales for soils, topography, hilliness, tree density, land condition, and average rainfall. No attempt has been made to review this aspect of the hydrologic effects of grazing because of limitations of time.

3.2.4 EFFECTS ON LARGE CATCHMENTS

There has been one major study of the effects of conservation practices on the water yield of large catchments, and a few lesser studies. The major study was the five-year Co-operative Water Yield Procedures Study (refs. 5,13) commenced in the U.S.A. in 1957 by the agencies most concerned with catchment yield - the Agricultural Research Service and the Soil Conservation Service of the U.S. Department of Agriculture, and the Bureau of Reclamation of the Department of the Interior.

The primary purpose of the study, as given in the Memorandum of Understanding between the sponsoring agencies, was "to develop and test procedures for evaluating the effects of watershed treatments on the yield of streamflow". Emphasis in the study was placed on the water-deficient areas in western U.S.A. A Work Group of three engineers, one from each agency, was formed to make the study.

Various methods of analysis were investigated on annual, seasonal, monthly and storm-by-storm bases. Included were simple correlations and regressions; multiple correlations and regressions (linear and curvilinear); analyses of variance; time series studies; double mass diagrams; "before-and-after" comparisons; hydrograph analyses; and others. In all, some 75 basins in the western half of the U.S.A. were studied, and intensive analyses made of a few basins in the Great Plains area.

No statistical approach was found that would consistently assess effects of land treatment on streamflow from river basins, or even prove conclusively that such effects do or do not exist. In a few cases, streamflow seemed to be increasing. In others, it appeared to be decreasing. In all cases, streamflow fluctuated considerably due to climatic or other causes. The Group reported:

> "Much of the data regarding streamflow, watershed precipitation, rainfall intensities, land use, land treatment, and related factors are fraught with uncertainties. These are so great that it is believed it cannot ever be demonstrated satisfactorily by statistical analyses, and with only the types and characteristics of watershed, streamflow, and climatic data now generally available, that the conservation use and treatment of land affects water yield by streamflow."

Overall, the investigation demonstrated that a procedure, based only on statistically significant results obtained from studies of river basins and research catchments, could not be developed. Instead, the Group developed a "Rational Formula" (ref.13) which estimates the effects of a conservation programme on water yield by individual allowances on annual runoff for the areas of contour-tilled land, terraces, improved pastures, irrigated areas, drainage, and farm dam construction. The allowances are trial-and-error values derived to fit available U.S. data, and cannot be recommended for use in Australia without considerable study.

The effects of agricultural practices on runoff have been studied in Russia for about 30 years. Leont'yevskiy (ref. 158) reviews the results of studies which have been made, the consensus of opinions which have been taken from time to time, and current Russian thought on the question (refs. 159, 160, 163, 164). The following is quoted from his paper:

"Because of the great importance attached to the influence of these practices on flow, before drawing its General Plan, the S. Ya. Zhuk All-Union Planning, Surveying and Scientific Research Institute (Gidroproyekt) has called for the co-operation of several scientific research institutes in the study of this problem. From 1962 to 1965, these investigations were conducted by the Institute of Geography, USSR Academy of Sciences, the State Hydrologic Institute, and the Moscow Hydromelioration Institute, which reported their findings in the Gidroproyekt.

Along with their reports, the Institute of Geography published a book entitled "Principles of the Method of Studying the Water Balance and its Transformations" in 1963 (ref. 161) and the State Hydrologic Institute published "Standard for Taking into Account the Influence of Agricultural Forest Melioration on Flow" (ref. 162). The Institute of Geography held a seminar in 1962 and an all-union conference in 1963 on the "Water Balance and its Transformation". The State Hydrologic Institute also discussed this problem at the Scientific Council on "Water Resources and Water Balance"."

The term "influence of agricultural forest melioration" used by Leont'yevskiy includes comparisons of forested and grassed catchments, in addition to runoff comparisons from cropped areas, layland, and meadows. Leont'yevskiy reviews the opinions of those Russian hydrologists who believe that agricultural and forest melioration practices do not reduce average flow to any significant extent, and also the opinions of those who believe that changes up to 45% of the flow in some rivers are possible. He cites examples of estimates made by a number of specialists of the effects of agricultural practices on flow. His conclusion was as follows:

"The foregoing suggests that agricultural practices have no significant effect on the normal flow of large and medium rivers. Therefore, in determining their water resources for the next 10-20 years there is no need to introduce any reducing corrections. This solution was adopted by the Hydrologic-Water Management Section of the Technical Council of the Gidroproyekt as it examined this problem with application to the General Plan for the complex utilization and protection of the water resources of the USSR. (This was also approved by experts who examined the "General Plan" in the autumn of 1967.)"

Nelson (ref. 8) cites two other studies of the effects of conservation works on runoff from large catchments, one an investigation of the water yield of the Brazos River, and the other a theoretical study of the Toronto Dam site catchment in Kansas.

The Brazos River investigation, reported by Carothers and Newman (ref. 83) was undertaken when it was thought that stock tanks and soil conservation practices may be adversely affecting the water yield available at Possum Kingdom. The catchment area above the dam is approximately 13,000 sq. miles and the average annual rainfall varies from 30 inches in the downstream areas to slightly less than 20 inches in the upstream areas.

The period of record used in the investigation was 1936-1953. During this period, the number of stock tanks each controlling an average area of 25 acres increased to 18,000. Soil conservation treatments were applied to 15.8% of the area and 18.2% of the area had been cleared of natural timber and cultivated.

During the period 1943-1953 the average runoff was estimated to be approximately 5.8% below that which could normally be expected. The reduction was considered to be the result of losses amounting to 6%, made up of 4.3% due to diversions at upstream reservoirs and 1.7% due to stock tanks. Soil conservation practices were considered to reduce the flow by 3.3%, but the clearing would produce a compensating effect by increasing the runoff by 3.9%. (The accuracy to one-tenth percent in the values given does not seem realistic to the present writer.) Floodwater retarding structures were not used on this catchment and no attempt was made to estimate possible reduction in peak flows caused by the treatment and tanks.

The Toronto Dam investigation, reported by Hartman and Wilke (ref. 84) was made to investigate the effects of land treatment, structures, and a combination of the two measures, on flood peaks from the 747 sq. mile catchment above the dam site on the Verdigris River. Land treatment included land use changes, improved farming practices, and conservation measures. Structures consisted of 141 headwater flood detention dams.

The effects of the treatment and structures were estimated in sub-areas of the catchment for four major storms of various recurrence intervals for which past records were available. Flows from the sub-areas were then flood routed down the main channel system to the dam site. From the results from the four floods, a graph was drawn showing the likely effect on flood peak of storms of any magnitude.

Because the mechanics of flood routing through dams and river channels are well known, it is possible to undertake routing studies, such as that described above, with reasonable certainty and accuracy of result. As a consequence, the method of investigation is attractive and similar studies on the effects of headwater reservoirs, both storage and flood detention, on peak rates of runoff have been made.

The most well-known study is that by Leopold and Maddocks (ref.87) who made a theoretical comparison of the relative merits of one large flood detention dam controlling a catchment of 600 square miles versus thirty small dams on tributaries, each with a catchment of ten square miles, and in total controlling 50% of the main catchment. This study showed that the tributary dams controlled flooding for only a short distance downstream and there was little reduction of flooding in the main river valley. As a generalization, the routing effect of a reservoir does not persist very far downstream and it is best to build flood control storages as close as possible to the area being protected.

Other studies of the effects of flood detention and storage dams in reducing peak rates of flow have been made by Zingg (ref. 104) and Hartman et al (ref. 85). These are dealt with in detail in the chapter on effects of dams.

One other study of effects on a large catchment is the investigation by Woodward and Nagler (ref. 86) of the effects of agricultural drainage on flood flows in the Upper Mississippi Valley. The study was made on the Des Moines and Iowa Rivers, a large portion of the watersheds of which have been covered with artificial drains subsequent to the establishment of stream gauging stations. The drainage operations involved the construction of tile drains, open ditches, and some straightening of stream channels, typical operations in drainage projects in the Upper Mississippi Valley.

A critical examination of the records of the two streams shows that during flood periods there has been no significant change in their behaviour which may be attributed to drainage. The total runoff from storms of like precipitation, the maximum rates of discharge, and the rain water storage conditions within the basins seem to have been unaltered by the extensive drainage operations. It is believed that if any of these factors had been changed by a measurable amount, such fact could easily have been detected by the analysis made in their paper.

Hartman and others (refs. 81, 85) studied runoff volumes and flood flows in the 250 square mile Washita River basin in Oklahoma. Systematic land changes occurred and conservation measures were progressively introduced from 1930. Comparison with the neighbouring Kiamichi River in which no changes occurred showed no effect on runoff volume due to conservation, land use or flood detention reservoirs.

However, reductions in flood flows were found after the installation of twenty-five flood detention reservoirs in 1962-1963, each with a storage capacity equivalent to $3\frac{1}{2}$ inches of runoff from its own catchment. Reductions in peak flows of 50% were attributed to the storages. Eighteen more reservoirs were planned as part of the overall project in this catchment.

In summary, the major effect that conservation programmes have on runoff from large river basins is that of reduction in flood peaks by flood detention storages. These storages occur in U.S. conservation programmes but are not common in Australia. The flood mitigating effect is most evident immediately downstream of each reservoir and the effect diminishes with distance downstream. The routing effect of such reservoirs is well understood and can be calculated with good accuracy given the necessary data.

The effect of conservation programmes on volume of runoff from large catchments seems very small, if it exists at all. The difficulty of demonstrating any effect on yield, which was encountered in the major Cooperative Water Yield Study in the U.S.A., and the lack of any conclusive results from Russian studies, suggests that any effect will not be large. At most, the effect on yield from large catchments is still within the limits of estimating runoff by current methods of analysis. There is little evidence to suggest that there might be major effects on yield which past studies have overlooked.

3.2.5 EXTRAPOLATING RESULTS FROM SMALL TO LARGE CATCHMENTS

One of the basic problems associated with hydrologic studies involving change in land use is that large catchments, several hundred square miles in area, are too big for experimental purposes and are too heterogenous for the effects of single factors to be evident. Effort has been concentrated on simple experiments on small catchments usually a few acres in area, but at the same time much doubt has been expressed about the validity of extrapolating results from small to large catchments. Hewlett, Lull and Reinhart (ref.88), in a defence of experimental watersheds, cite criticism by Slivitzsky and and Hendler (ref. 89), Ackermann (ref. 90), Panel on Watershed Research (ref. 91), Renne (ref. 92), and Reynolds and Leyton (ref. 93).

Kovacs (ref. 94) suggests that catchments more than 100 sq.km. (40 sq. miles) in area behave differently to catchments less than 50 sq. km. (20 sq. miles). Sharp, Gibbs and Owen (ref. 13) in reporting results of the 5-year Cooperative Water Yield Procedures Study state that "No means has yet been discovered for directly translating small-watershed-research results to large complex watersheds". In the earlier 2-year Progress Report, (ref. 5), these authors noted that, in arid and semi-arid areas, the volume of measured runoff from small research catchments is generally greater than from larger catchments. They attributed the differences to variations in precipitation, channel losses, and differences in the amount of area in cultivation.

Some of the results which have been obtained from unit-source watersheds illustrate the problem. A unit-source area is presumed to have relatively homogeneous soils and vegetation cover, uniform precipitation, and geologic influences on the surface outflow (Kincaid et al, ref. 95). Amerman (ref. 96) defines a unit-source area as "a sub-division of a complex watershed which, ideally, has a single cover, a single soil type, and is otherwise physically homogeneous".

The underlying concept is that complex watershed runoff is essentially a summation of the runoff contributions from its component unit-source areas. Unit-source areas that are sufficiently alike are assumed to act in a similar manner hydrologically when they are subject to storms that are alike. Amerman says:

> "by prediction and combination of unit-source area runoff, it should be possible to predict runoff from ungauged complex watersheds. In this manner, the integrated effects of runoff of various combinations on land use changes on a complex watershed may be calculated".

In the experiment report by Amerman, storm-by-storm runoff from 10 unit-source areas did not agree with observed runoff on a 76 acre catchment at Coshocton, Ohio, although a linear regression equation between computed and observed runoff had a correlation of 0.99. Observed runoff tended to be about 30% higher than computed runoff. Amerman suggested that the disagreement in direct comparison may be due to:-

(1) interflow

(2) partial area runoff

(3) influence of runoff from upslope areas upon runoff production on downslope unit-source areas.

Mustonen and McGuinness (ref. 103) report on a study of the difference in the evapotranspiration losses from a lysimeter and that from a whole catchment, as determined by water-balance studies of two catchments of 43 acres and 303 acres. This study showed that the lysimeter measurements were substantially higher than the calculated evapotranspiration losses from the catchments, the ratio of catchment losses to lysimeter losses being in the order of 0.7.

Transmission loss in stream channels has been reported in a number of publications. Keppel and Renard (ref. 97) report on a study made in the 14-inch rainfall area of south-eastern Arizona. Their study was made on a 58-sq. mile drainage area being a tributary of Walnut Gulch. In a very dry channel system, where runoff occurred only as a result of intense summer thunderstorms, transmission losses of 25 acre feet per mile of channel were recorded.

Laurenson (ref. 98) found substantial losses in four floods on two major rivers in Australia. Figures in his report show losses of 12, 36, and 95 acre feet per mile on the Darling River and 46 acre feet per mile on the Murrumbidgee River.

Sharp and Saxton (ref. 99) studied 57 selected flood events on 18 rivers in the Great Plains of the U.S.A., and reported that transmission losses averaged 40% of flood flows between upper and lower gauging stations averaging 53 valley miles apart. Losses of over 200 acre feet per mile, approximately 75% of flood volumes, were found.

Results from the Soil Conservation experiments at Parwan, Victoria, by Dunin (ref. 14) show significant differences in runoff between a 210 acre catchment and several 4-acre catchments nested within it. The differences appear to be due to transmission losses.

Recently Chapman (pers. comm.) has found that a substantial part of the errors of prediction found in current lumped-input catchment models can be explained by rainfall variation over catchments of only a few tens of square miles in area. Variations in rainfall, coupled with variations in evapotranspiration loss by variations in slope and aspect of the ground surface, make it appear that large heterogenous catchments must be analysed in component parts for accurate rainfall-runoff relationships. There seems to be little opportunity for directly extrapolating results from a single rainfall runoff system on a small catchment to any large area where substantial heterogeneity in topography and rainfall input exists.

Finally, mention should be made of the variations which may exist among small catchments, even those which appear similar and are located together in an apparently homogeneous landscape. Sopper and Lull (refs. 100, 101, 102) analysed data from 137 catchments less than 100 square miles in area in the northeast U.S.A., for annual and seasonal yield, flow duration and peak flow frequency. The catchments represented seven major physiographic units; all had continuous records from 1940 to 1957; none were affected by regulation and diversion. Generally, there appeared to be as much variation between catchments within a region as between regions.

Although no similar analyses have been made in Australia, data available from groups of small catchments such as those operated by the Soil Conservation Authority of Victoria at Parwan, also show considerable variation in runoff. The natural variation which exists among small catchments makes it very difficult if not impossible to select a "representative" small area whose runoff patterns can be extrapolated with accuracy to the whole region in which it is located.

3.2.6 SUMMARY OF EFFECTS ON QUANTITY OF RUNOFF

Storage dams such as those used for water supply or irrigation on farms have an obvious influence in depleting the total amount of runoff from a catchment. However, the most common construction in soil conservation programmes, i.e. banks or terraces, appear to have little effect on catchment yield. The available evidence is variable to the extent that some increases in runoff have been recorded following the installation of terraces. These works do appear to have an effect in reducing the peaks of small floods on small areas but the evidence is qualitative and not yet developed to the stage of general design procedures.

The practices which appear to be significant in affecting catchment yield are those which have a direct effect on evapotranspiration loss. Fallow, which eliminates evapotranspiration loss and results in higher soil moisture levels, usually results in more runoff than from grassed or cropped areas. Where a change in vegetation occurs that incorporates a change in root depth, the deeper rooting plants can extract more moisture than the shallow rooting plants and so create greater soil moisture deficiencies. There is evidence to suggest that some differences in runoff from areas with different pasture species could be due to differences in root depth. Other differences in runoff between cropped and pastured areas appear to be more related to differences in evapotranspiration use of water than to any other component of the hydrological process.

The evidence for differences in catchment yield due to controls on evapotranspiration loss are restricted to small areas. All studies which have been made of the effects of conservation works on large catchments have failed to adequately define any significant effect on yield. There is little evidence to suggest that any major influences on the water yield of large catchments could be still undetected by the studies already made.

The effect of conservation structural works on flood flows from large catchments is, by comparison, fairly well established. The structural works which are significant in reducing flood peaks are detention dams and river channel improvements to mitigate overbank flow. The effect of these works is localised to the extent that the effect of flow reduction is most evident immediately downstream of a detention dam and the effect diminishes with distance downstream. The effect of channel improvement is also localised and can be the cause of increased floods downstream of the works under particular conditions. There is no evidence to suggest that agronomic practices or conservation terraces have much effect on major floods on large catchments.

There is a constant problem in extrapolating research results from small experimental areas to large heterogeneous catchments. Variations in rainfall, evapotranspiration loss, infiltration, and runoff, over different parts of a catchment, and such factors as interflow and transmission losses, make any extrapolation very difficult and unreliable. The problem of extrapolation is an area of research still virtually untouched.

3.3 EFFECTS OF AGRICULTURAL AND CONSERVATION PRACTICES ON QUALITY OF AVAILABLE WATER

3.3.1 Sources of Pollution

Agricultural activities can have much greater effects on the quality of surface runoff and groundwater recharge than on the quantity of water. Bacteriological contamination from animal wastes has long been recognised as a source of pollution, and there are restrictions on many agricultural activities on catchments providing town and city water supplies in Australia.

More recently, problems have arisen from the resides of long-lived pesticides which are leached from agricultural lands. Nutrients can also be leached from lands where excess amounts of fertilizers are applied, and problems of weed growth and eutrophication can result where the nutrients are accumulated in rivers, streams, or reservoirs.

The major sources of pollution of water supplies from rural land use are animal wastes, fertilizers, pesticides, plant residues, and saline waste water from irrigated areas. (Production of sediment is another type of water pollution.) Saline waste water is dealt with in the chapter on "Irrigation and Drainage" and is not treated here. The other types of pollution are reviewed in the following sections which cover both surface runoff and groundwater aspects.

3.3.2 Animal Wastes

Animal wastes are considered as all wastes associated with producing animal products. These include animal excreta (solid and liquid), litter or bedding, cleaning materials, chemicals used for pest control, cleaning water, spilled feed, and waste carcasses. A number of studies (refs. 106-111) have included determinations of the amounts and strengths of animal wastes. The amount and strength of wastes produced by an animal depends on the type, breed, sex, age, size, feed and any additives of the ration, health and the environment of the animal. Environmental factors which include temperature, humidity, light, antecedent moisture, rainfall and time affect the rate and amount of degradation of animal wastes.

Farm animals in the U.S.A. produce over 1 billion tons of fecal wastes per year (ref. 112). The liquid wastes exceed 400 million tons. When bedding and waste carcasses are included, the annual production of animal wastes is nearly two billion tons. As much as 50% of the waste may be in concentrated production areas. Four hundred cows in a mechanised dairy will produce about 14 tons of solid wastes and $4\frac{1}{2}$ tons of liquid wastes daily; 10,000 cattle in a feedlot operation 260 tons of solid waste and 100 tons of liquid wastes daily; and 100,000 fowls in a battery poultry enterprise about 5 tons of waste per day.

In Australia, Henry (ref. 113) has reviewed the problem of disposal of farm manure in Queensland. The estimated amount of 66 million gallons of dung and urine per day produced by 7.400.000 beef and dairy cattle would be only $1\frac{1}{2}$ pints per acre if uniformly spread, but high concentrations of animals, particularly pigs and poultry, cause problems. The Department of Local Government in Queensland is responsible for pollution control and is undertaking catchment surveys and water quality surveys in 50 rivers, mainly coastal but including some inland rivers (ref. 114).

Several major symposia in the U.S.A. have been devoted to livestock wastes management. The National Symposium on Poultry Industry Waste Management (ref. 115) includes papers on the nature of the poultry waste problem, waste characteristics, and various manure treatment devices including incinerators, anerobic lagoons, dehydrators, and aerobic lagoons. The odour, disease, and water pollution aspects are discussed. The Second National Symposium on Poultry Industry Waste Management (ref. 116) presents similar material and also discusses related legal problems.

The farm animal waste problem is also considered in the National Symposium on Animal Waste Management (ref. 117) from several points of view. Data on the characteristics of bovine wastes, duck processing wastes, and feedlot runoff are included. Also, many aspects related to disposal, treatment and utilization of animal wastes were discussed.

Distribution onto agricultural land is still the most widely used disposal technique for animal manures. McGauhey et al (ref. 118) have prepared an extensive literature review on the use of soil as a waste treatment system. Included are sections on infiltration and percolation, soil clogging, treatment results, and various engineered systems using the soil. A bibliography of 289 entries is included.

Animal wastes contain large populations and varieties of bacteria and viruses some of which may be pathogenic to man. The wastes also contain plant nutrients in varying amounts, an assortment of organic and inorganic matter in various stages of decay, and salts that are sometimes in abundance. Wadleigh (ref. 112) cites nitrogen as the contaminant that presents the greatest problem in groundwater pollution by animal wastes.

Nitrate in drinking water can cause methemoglobinemia in babies (blue babies). It is also toxic to livestock and may be passed on in milk. Bosch et al (ref. 122) report that nitrates in farm well-water caused 139 cases of infant methemoglobinemia between 1947 and 1950, including 14 deaths in Minnesota alone. Wadleigh (ref. 112) cites an instance where 3100 ewes and 300 cows experienced abortions in a single livestock operation shortly after drinking high nitrate water.

Smith (ref. 123) reports on extensive studies of nitrate content of 6000 rural water supplies in Missouri. He concluded that infiltrates from feedlots were the main source of nitrate in groundwater. Other sources may contribute nitrate and these include sewage and septic tank effluent, fertilizers, high organic soils and areas of luscious plant growth and decay.

Miner et al (ref. 124) have shown that feedlot runoff is a source of high concentrations of bacteria normally considered as indices of sanitary quality. Henderson (ref. 125) has evaluated data to show the high potential and actual pollution in streams caused by animal wastes. Smith and Miner (ref. 126) obtained water quality measurements on streams and rivers subject to pollution from feedlot runoff and found that considerable lengths of the watercourses were devoid of oxygen due to the pollution. Decker and Steele (ref. 127) list the infectious diseases organisms common to man and other animals.

Gatehouse (ref. 120) discusses the various aspects of farm waste disposal in England and Taiganides (ref. 110) describes management practices of Europe and India. Golueke and McGauhey (ref. 134) have presented a comprehensive report on solid wastes management which includes a discussion of the agricultural solid waste problem and the urban-rural interface with regard to waste management. Animal manures, dead animals and crop residues are listed as the major solid agricultural wastes.

Recently, some excellent reviews of the animal waste problem have been prepared. Loehr (ref. 135) and Loehr and Agnew (ref. 136) have summarised the state-of-the-art in managing animal wastes and have reviewed the magnitude of the problem as it occurs in the U.S.A., the pollution already caused and potential pollution from animal wastes, feasible treatment processes and major problem areas. Robbins and Kriz (ref. 137) have prepared an extensive review of the relation of agriculture to groundwater pollution and their report includes animal wastes as one of the principal sources of pollution.

3.3.3 Fertilizers

The rate of use of chemical fertilizers on agricultural lands is increasing at a very rapid rate. Figures cited by Robbins and Kriz (ref. 137) show that consumption of major fertilizers in the U.S.A. is doubling about every ten years. Wadleigh (ref. 112) points out that usage is still well below potential and gives data to show that the use of nitrogen and phosphate fertilizers per acre of land in the Netherlands is about ten times that of the U.S.A.

The nitrogen used is largely in forms such as ammonium sulphate, anhydrous ammonia, ammonium nitrate, sodium nitrate, calcium nitrate and various ammoniated phosphates and super-phosphates. These forms are typically highly soluble. Where precipitation or irrigation is periodically in excess of plant requirements, downward-percolating water carries with it nitrogen compounds from the fertilizers.

Nitrogen is the element most involved in pollution due to fertilizers. Feth (ref. 139) has made a comprehensive review of nitrogen compounds in natural waters and he lists the following as major sources: precipitation, fixation by micro-organisms in soil and water, decaying organic matter, animal and industrial wastes, as well as probably undiscovered sources in consolidated and unconsolidated rocks. Allison (ref. 140) quotes an attempt to make a nitrogen balance sheet for harvested lands in the U.S.A. (see below). The items listed for erosion and leaching are of special interest as potential sources of nitrogen in surface water and groundwater.

Additions	Nitrogen lb/acre/yr.
Rain and irrigation	4.7
Seeds	1.0
Fertilizers	1.7
Manures	5.2
Symbiotic nitrogen fixation	9.2
Nonsymbiotic nitrogen fixation	6.0
	27.8
Losses	
Harvested crops	25.1
Erosion	24.2
Leaching	23.0
	72.3
Net annual loss	44.5

A Task Group report of the American Water Works Association submitted by the Task Group chairman (ref. 141) discusses the sources of nitrogen and phosphorous in water supplies in the U.S.A. They conclude from "order of magnitude estimates" that agricultural runoff is the greatest single contributor of nitrogen and phosphorous to the nation's water supplies. O'Connor (ref. 142) has reviewed the role of agriculture in affecting water quality in rivers and lakes in New Zealand. He cites measurements and estimates which have been made of nutrient concentrations.

3.3.4 Pesticides

Pesticides may be classified according to their use as insecticides, herbicides, rodenticides, miticides, nematicides, or fungicides. They can also be classified according to their origin:-

1. Mineral origin - includes arsenical and inorganic compounds containing sulphur, copper and fluorine.

2. Botanical origin - includes nicotine, pyrethrum and redquill.

3. Synthetic origin -

   a. Insecticides - chlorinated hydrocarbons (dieldrin, endrin, D.D.T., lindane)
      - organic phosphorous compounds (parathion, malathion)

   b. Phenoxyalkanoic acid herbicides (similar to chlorinated hydrocarbons) - 2.4 D, 2.4.5-T

   c. Miscellaneous compounds - e.g. carbamates, dithiocarbamates.

The use of chemicals such as sulphur for pest control dates back to the beginnings of recorded history. But the pesticidal properties of D.D.T. were not discovered until 1939 and organo-phosphates were first marketed about 1945. Since then the production and use of synthetic pesticides has increased enormously. While the above classification appears simple, the committee of enquiry appointed by the Premier of Victoria to enquire into the effects of pesticides, listed 376 pesticides available in that State at the time (ref. 143).

The first awareness of pesticides as a water pollution problem came in 1950 in the U.S.A. when insecticides washed from cotton fields produced extensive fish kills in 14 tributaries of the Tennessee River in Alabama (ref. 144).

An example cited by Randall (ref. 145) illustrates the magnitude of the problem. During the winter of 1963-64, a massive fish kill which resulted in the deaths of about 175,000 fresh-water and 5,000,000 salt water fish occurred on the lower reaches of the Mississippi River. Investigating officials of the U.S. Public Health Service reported that tests showed the river to be contaminated with endrin, an insecticide with a very high toxicity to fish. Further tests identified the presence of endrin in the blood and muscles of the dead fish.

Several months after the Mississippi River fish kill, officials in Memphis, Tennessee, discovered that a large section of sewer system located near a factory manufacturing pesticides was clogged with several thousand pounds of endrin in deposits up to four feet deep. A portion of the sewer, which empties into the river, had to be closed off and abandoned (see also Beerman, ref. 146 and Novack and Rao, ref. 147). Case histories of fish kills caused by runoff from areas treated with pesticides have been reviewed by Cottam (ref. 138).

Unfortunately, the same characteristics that make DDT and other chlorinated hydrocarbon compounds successful as pesticides - wide range toxicity and extreme persistence - also make them dangerous from a water pollution view point. Most of these are very resistant to natural degradation having effective lifetimes in the order of 10 years. Westlake and San Antonio (ref. 148) reported that 50% of pesticides could be recovered from the soil six years after the initial application.

Johnston et al (ref. 149) analysed effluents from irrigated lands for pesticide residues in the San Joaquin Valley of California. Relatively small quantities of chlorinated hydrocarbon residues were found in tile drainage effluent but higher concentrations were found in effluent from open drains where both surface and subsurface waters were collected. There were traces of residues in the irrigation water supplied to the area. Relatively large concentrations of residue were found in the surface soil of the area studied even where no pesticides had been applied directly to the soil.

Bailey and Hannum (ref. 150) studied the distribution of chlorinated hydrocarbons and thiophosphate pesticides in waters, sediments and aquatic organisms in California. The results show that pesticide concentrations are directly related to agricultural practices and concentrations are highest where agricultural development is greatest. The temporal distribution in surface waters was related to agricultural drainage practices and to rainfall and runoff patterns. Analysis of aquatic organisms supported the concept of successive parts of a food chain passing on higher concentrations of pesticides. Pesticides were found to be concentrated in both organisms and in sediments, particularly fine grained sediments. Cope (ref. 151) also discusses the contamination of freshwater ecosystems by pesticides and the eventual fate of the pesticides.

Chlorinated hydrocarbons have no solubility in water. When these pesticides are washed into streams, they remain in the flow until absorbed onto soil particles or ingested by aquatic organisms. It is the ability of aquatic organisms to store and concentrate the pesticides in their body tissues that is of such importance. The following illustrates the increasing concentrations of TDE pesticide obtained from a food chain in a lake in California.

Water
0.02 ppm
↓
Plankton
5.3 ppm
↓
Small Fish
10.0 ppm
↙ ↘
Predatory Fish 1,700 ppm | Predatory Birds 1,600 ppm

In many countries, public concern about the effects of pesticides used on agricultural lands has stimulated governments to establish committees of enquiry or review. In the United Kingdom, there have been several enquiries beginning in 1951 and then in 1953, 1955, 1961 and two in 1964. Several investigations have been made in the U.S.A. and others in Canada and by United Nations organizations such as F.A.O. and W.H.O.

The Report of the Committee of Enquiry appointed by the Honourable the Premier of Victoria to enquire into the Effects of Pesticides (ref. 143) gives a good review of the situation in Australia and the problems related to water quality. In the discussion of the Persistence in Water of Pesticides, the Committee reported:-

> "A special problem is posed by the contamination of both fresh and saline water. Chemicals such as chlordane, heptachlor, D.D.T. (and its metabolites), toxaphene and rotenone may persist in water. However, the persistence of chemicals in certain aquatic organisms may be of even greater significance. Some invertebrate and vertebrate organisms, whilst demonstrating a progressive accumulation of chemicals, show no apparent ill-effects. These organisms constitute the aquatic food chain. The short life cycle of many aquatic organisms poses a further problem as yet inadequately examined anywhere. There is little information about levels of persistent chemicals in bottom muds and sands and of their transfer from this environment.
>
> In Victoria no information is available on contamination of water supplies although fish mortalities from time to time in some streams are an indication that some

pesticides from farm lands are getting into water which may be drawn off for town supply."

In its Recommendations, the Committee proposed that:-

"The Fisheries Act and Stream Pollution Regulations under the Health Act should be extended to prevent -

(i) any pesticides from entering a stream, except in approved circumstances and conditions;

(ii) the preparation of any spray mixture in a stream or within 2 chains of the edge of a stream;

(iii) the washing of bags or any other container originally containing any pesticide in a stream;

(iv) the depositing of any package containing or having contained any pesticide in a stream or within 2 chains of the edge of a stream; and

(v) spraying or dusting particular pesticides from the air within a prescribed distance from the edge of the stream."

3.3.5 Effects on Groundwater

There is no evidence that agricultural or conservation practices have affected groundwater recharge in Australia except in irrigated areas and where change in plant cover has changed evapotranspiration loss.

Generally, the major problem that has appeared in the U.S.A. is one of groundwater pollution from agricultural activities. It seems probable that similar problems could develop in Australia as agriculture becomes more intensive and the current situation in the U.S.A. might be a guide to future developments here. A review of U.S. work is set out in the following.

Robbins and Kriz (ref. 137) have reviewed available information on the relation of agriculture to groundwater pollution and their paper includes a bibliography of 97 published reports. These authors list the 5 major categories of agricultural pollutants as animal wastes, fertilizers, pesticides, plant residues and saline irrigation-waste waters.

If an agricultural pollutant does not attenuate appreciably or decay rapidly, it may pass from the land surface through the zone of unsaturated soil to groundwater, then into surface streams and to the sea. Two phenomena govern the movement of waste substances in soil systems (refs. 153, 154). One is diffusion that results from variations in waste concentration with position in the soil system; the other is convection by water which drags the waste along.

According to LeGrand (ref. 153) the movement of contaminants through the zone of aeration tends to be vertical. Lateral dispersion above the water table is generally small unless appreciable amounts of waste water are applied to the soil in a localised area or the land surface is relatively steep. If the latter occurs, the water table may rise as a mound and cause radial dispersion of the pollutant.

Lateral dispersion predominates in the saturated zone and pollutants move in the same general direction as the groundwater. A knowledge of groundwater flow patterns may be sufficient to predict the behaviour of some contaminants. LeGrand found that reports on rates of water movements in unconfined aquifers were scarce. He also reported that movement of groundwater is much greater just below the water table than at greater depth. Where groundwater movement is slow, contamination can become very serious before the problem becomes obvious.

Information on the movement of various pollutants in the groundwater system was assembled in the proceedings of a symposium on groundwater contamination (ref. 155). Deutsch (ref. 156) presented descriptions and illustrations of a variety of problems of groundwater pollution. An earlier report (ref. 157) cited by Robbins and Kriz describes laboratory and field investigations of the travel of contaminants in aquifers.

A major problem in determining criteria for groundwater pollution is the difficulty in predicting or even approximating the changes in a real extent of contaminated zones with time and with concentration. Two factors to consider are the tendency for enlargement of the zone of pollution as more wastes are added and water disperses them; and the tendency for the size of the zone to be retarded as wastes at the periphery are continuously being attenuated.

The addition of wastes to a soil system may change its waste-handling characteristics (ref. 118). Plugging of soil pores may result in significant changes in the rate of water movement. Biodegradation of excessive amounts of organic wastes may deplete the oxygen in an aquifer and change the decomposition from aerobic to anaerobic.

The ultimate fate of agricultural wastes when incorporated into a soil system depends on the physical, chemical and biological environments within the system. Because air, plant, animal, soil, groundwater and surface waters are generally related, the overall behaviour of new agricultural wastes in the total environment must be understood before control measures can be established with reliability.

LeGrand (ref. 152) proposed a series of questions based on the pollution cycle that must be considered for each particular situation. The questions concern the waste itself, the hydrogeology of the area and the human aspects. The questions are as follows:-

Wastes :

- Is the release of the waste a single slug or mass?
- Is the release sporadic or continuous?
- What is the concentration?
- Is it liquid or solid?
- If solid, to what extent is it leached?
- If liquid, is the quantity enough to change the normal groundwater flow pattern?
- Does the waste contain a single contaminant or a mixture of contaminants?
- What is the relative degree of toxicity or objection?
- What is the attenuation habit of the critical contaminant by dilution in water, decay with time, or sorption on earth materials?
- Is the past history of waste release in the area important?

Hydrogeology:

- What are the porosity and permeability characteristics in the area?
- Is there soil and other consolidated material to much depth?
- Is dense rock at the land surface?
- Is the surface permeability poor or is liquid disposal so great that the contaminants will be shunted to the land surface and not have a conventional underground movement?
- What are the sorptive capabilities of materials through which the contaminants will move?
- What is the highest seasonal level of the water table and its fluctuations through the year?
- What is the approximate course of the groundwater flow?
- Can the groundwater divide be distinguished?

Human Aspects:

- What man-made operations need consideration?
- What is the proximity of well sites to waste sites?

To what extent has the natural groundwater flow system been modified by man?

What can be anticipated in the future about changes in groundwater flow and water supply and waste disposal practices?

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CHAPTER 4

FORESTS

4.1 INTRODUCTION

A continuous cover of mature forest is probably the best protection that a water supply catchment can have to minimise erosion and turbidity. However, in Australia, forestry is practiced much less as protection forestry than for commercial production of timber. There are conflicts of interest when forestry operations have a deleterious effect on water quality or when water supply authorities stop harvesting of timber or even fire-control operations on catchment areas.

The role of forests in protecting against erosion has been accepted for a very long time. Kittredge (ref. 1) reports that as early as 1215, Louis VI of France proclaimed an ordinance entitled "The Decree of Waters and Forests". In 1342, a community in Switzerland reserved a forest for protection against avalanches and between 1535 and 1777, protection forests were proclaimed in 322 instances.

Early opinion held that the effects of forests on catchments were beneficial becuase of increased infiltration into the soil, greater moisture storage in the humus and litter layers, reduced flood peaks and longer sustained low flows, attenuated snowmelt and prevention of erosion. In 1909, Chittenden (ref. 2) published a treatise on the subject and from the available evidence, he stated the following seven conclusions:

(1) The bed of humus and debris.....retains precipitation.....it acts as a reservoir moderating the runoff from showers and mitigating the severity of freshets.

(2) The above action fails altogether in periods of prolonged and heavy precipitation, which alone produces great general floods....Not only does the forest at such times exert no restraining influence upon floods, but.... may actually intensify them.

(3) In periods of extreme summer heat, forests operate to diminish the runoff....

(4) The effect of forests upon the runoff resulting from snow-melting is to concentrate it into brief periods and thereby increase the severity of freshets....

(5) Soil erosion does not result from forest cutting in itself, but from cultivation, using that term in a broad sense....(meaning a variety of methods for disturbing the soil).

(6) As a general proposition, climate and particularly precipitation, has not been appreciably modified by the progress of settlement....

(7) The percentage of annual runoff to rainfall has been slightly increased by deforestation and cultivation.

Chittenden's paper elicited considerable response with 22 written discussions contributed. Soon afterwards, in 1912, Zon (ref. 3) put together an exhaustive review of available facts for the U.S. Senate. Other studies such as those by Forsling (ref. 4) and Munns et al (ref. 5) in 1933 have assembled the available knowledge of the time. In 1948 Kittredge traced the history of thought on forest influences and gave a broad review of the subject. The I.A.S.H. Symposium of Hannoversch-Munden (ref. 6) in 1959 was devoted to "Water and Woodlands" and 35 relevant papers were presented. Storey, Hobba, and Rosa (ref. 7) set out more recent knowledge in 1964 in the "Handbook of Applied Hydrology".

The most comprehensive review of activities and results of forest hydrology studies was made in 1965 at the International Symposium on Forest Hydrology held at Pennsylvania, U.S.A. Proceedings of the symposium which included 80 papers have been published with discussion (ref.10). Papers presented describe forest hydrology research in 20 countries including a review of Australian activities by Costin and Slatyer (ref.12). The countries whose work was reviewed at the symposium were Austria, Australia, Belgium, Canada, Czechoslovakia, Denmark, East and Central Africa, Finland, Germany, Greece, Israel, Japan, Netherlands, New Zealand, South Africa, Sweden, Switzerland, Taiwan, United Kingdom and U.S.A.

Russian studies of forest hydrology have been extensive although there was no contribution from USSR at the Pennsylvania symposium. Rakhmanov (ref.13) has reviewed and summarised 247 Russian papers and reports, as well as 87 in other languages, dealing with the role of forests in water conservation. Another review has been made by Molchanov (ref. 14). Several papers (refs. 21-23) at the I.A.S.H. symposium on "Water and Woodlands" also describe Russian work.

There have been many annotated bibliographies prepared dealing with publications on forest hydrology. In the U.S.A., Lull (ref. 15) has prepared an annotated bibliography of publications on watershed management research by the North-eastern Forest Experiment Station which covers 156 publications. Gleason (ref. 16) has prepared a similar documentation of 204 publications on erosion, streamflow, and water yield by the California Forest and Range Experiment Station. Price (ref. 17) reviews literature on watershed management in the Southwest. In 1930, Lowdermilk (ref. 20) prepared a bibliography on the influence of forest litter on runoff, percolation and erosion. This lists early studies related to this aspect of forests.

Australian research activity in forest hydrology has not been extensive although a wide range of subjects have attracted interest. The effects of converting native forest to grassland and to pine plantation; the effects of fire on water quality and erosion; the relation of turbidity in water supplies to forest roads and logging operations; have been studied. However, with the exception of the Watershed Management Section of the Forest Research Institute in Canberra, research activity in Government organizations has been more connected with the interests of individual persons than with any systematic programme. Most states have one or two research catchments and usually only one person actively dealing with forest hydrology.

The published reports of Australian studies give a good summary of the problems that have attracted interest in particular areas. But the greater number of overseas reports, particularly those from the U.S.A., are of more value in evaluating the effects of forests on water yield, floods, erosion and turbidity. An illustration of the problems that are relevant in Australia is given by McArthur and Cheney (ref. 11) who suggest that the forest management practices which may have an effect on catchment behaviour include -

(a) timber utilization and silvicultural treatment which result in a reduction of the stand density,

(b) clearing of indigenous vegetation and its replacement with an alternative forest crop, generally an exotic coniferous species,

(c) management designed to increase the density of the existing forest cover by protection from fire and grazing and by enrichment planting of native or exotic species,

(d) grazing,

(e) fire.

These authors also note that "most forest practices such as roading, logging, control burning, and plantation clearing will produce increased erosion and sedimentation if carried out in an unplanned and haphazard manner without due regard to the primary objective of management which is to prevent any reduction in water yield and quality. With careful prescriptions the amount of sediment originating from areas where forest operations are in progress can be frequently reduced to lower values than that from undisturbed areas."

The aspects of forest effects on hydrology which are considered in this report are dealt with under the following headings:

1. Effects of clearing, thinning, afforestation, species, etc. on water yield.
2. Effects on floods.
3. Effects on water quality, including turbidity and erosion.
4. Effects of fire.
5. Snow management.

4.2 EFFECTS ON YIELD

4.2.1 Clearing and Afforestation

The change of plant cover when trees are cleared from a forested catchment and replaced with grass is of considerable concern to Australian authorities because of the vast areas which have been cleared since the beginning of white settlement. It has also attracted considerable attention from foresters in other countries and there have been many experiments made to assess the hydrologic effects of clearing, or conversion from trees to grass.

This aspect has been dealt with in detail in an earlier chapter. The results of the review which has been made may be summarised as follows:-

a. Conversion of a catchment cover from deep rooting trees to shallower rooting grasses usually results in an increase in surface runoff, or in groundwater recharge, or possibly both.

b. Afforestation of a grassed catchment will result in the reverse effect i.e. a decrease in surface runoff or groundwater recharge.

c. The reason for the change appears to be mainly related to the difference in root depth from which the different plants can extract moisture from the soil. Trees, which have opportunity to extract more soil moisture than grass because of their deeper root system, can create greater soil moisture deficiencies when there is sufficient water demand. This results in less groundwater recharge, more abstraction from following storms, and less surface runoff. Interception, infiltration and differences in potential evapotranspiration rates appear to be much less significant than the differences in soil moisture which is available to the plant.

d. The effects of clearing are disguised to some extent by factors such as slope and aspect of the catchment which also affect evapotranspiration loss. There is no simple or single relationship which can be used to express the results of clearing on water yield and to date, no attempt has been made to use mathematical models for simulation of the processes involved.

An opposite effect has been found for special conditions in Russia. Pereira (ref. 24) reports that, under a rather unique set of conditions which occur over a wide area of European Russia, forest cover gives a higher water yield than does farmland. The special conditions are:-

(i) that most of the annual precipitation occurs as snow,

(ii) that major runoff events in each year are due to snow melt,

(iii) forest root-range is confined to a shallow layer of about one metre depth.

This experience is a warning that the general conclusions a. to d. above may not hold in some areas of the alpine country in Australia.

4.2.2 Thinning

Some results of thinning experiments were reviewed in the earlier chapter on "Clearing". Generally, it was found that when only part of a catchment is cleared, the resulting increase in runoff is less than would be expected if the whole catchment was cleared, and in proportion to the percentage of the area cleared.

There is one area in Australia where an opposite view is held, and where the management of major water supply catchments is involved. The Melbourne and Metropolitan Board of Works have opposed logging of mature trees from the catchments providing Melbourne's water supply on the grounds that young growing trees will take more water than the mature trees that they replace (see discussion of ref. 61, p.107).

There is not much evidence in the literature to support this view. The review by Hibbert (ref. 25) of 39 paired catchment experiments on water yield gives some evidence that yield increases as the stand of trees is thinned. Douglass (ref. 26) reviews nine studies of the effect of varying stand density on evapotranspiration loss and he concludes "In many cases, failure to sample the entire root depth and inability to account for drainage loss prevent direct comparison of evapotranspiration rates, but a tendency is clear - reducing stand density reduces evapotranspiration and the greater the density reduction, the greater the evapotranspiration reduction."

Kittredge (ref. 1 pp.242-243) in his substantial review of forest influences put forward an opinion that thinning would reduce water usage and increase water yield. Colman (ref. 27) held the same opinion.

The results which are most relevant to the Melbourne catchment areas come from Brookes and Turner (ref. 28) who report on a study of the water yield of catchments covered by Eucalyptus regnans on the Dividing Range about 40 miles from Melbourne. They concluded that "there is some evidence for the view that in young forest of this type the water yield decreases with increase of stand density."

At the present time (jan. 1970), the Melbourne and Metropolitan Board of Works is establishing experimental catchments to study the hydrological effects of forest management in areas representative of their major water supply catchments.

4.2.3 Effects of Change of Species

The possibilities of differences in water use between hardwood and coniferous forests have attracted the attention of foresters in a number of countries around the world. Douglass (ref. 26) reviews comparative studies made by Lull and Axley (ref. 29), Metz and Douglass (ref. 30), Moyle and Zahner (ref. 31), Patric (ref. 32), and Zahner (ref. 33). His conclusion from this review was that "well-stocked forest vegetation appears to use water at about the same rate regardless of species".

One result showing a difference in water use between coniferous and hardwood species was attributed to differences in root depth. Douglass comments that "As with grass, variations in rooting depth seem to cause the only significant difference in seasonal evapotranspiration from pine and hardwood stands."

In South Africa, the natural hardwood forest occurs only in small remnants but large areas have been afforested with exotic species. Establishment of plantations of exotic species began towards the end of the 19th century and Wicht (ref. 34) has estimated that the area of exotics in 1955 was about 813,000 hectares (2 million acres) and that this would be extended to an upper limit of 1,382,000 hectares (3.4 million acres) by the end of this century.

Controversy in South Africa over the exotic plantations arose from fears that the forests would dry up water supplies, exhaust the soil and promote erosion. Wicht traces the development of interest and experimentation (see refs. 35-38) and reviews opinion held in South Africa on the water use by different species. He quotes from a 1949 report on "Forestry and Water Supplies in South Africa" (ref. 39) as follows:-

> "....reliable results from controlled analytical research are not yet available. The following conclusions therefore merely attempt to summarise briefly the least problematic results of general experience and observation.
>
> 1. Plantations of exotic trees, grown to timber size, will probably not use more water than indigenous forests, if they are on comparable sites.
>
> 2. Plantations of exotics and indigenous forests, will probably use more water than fynbos (sclerophyll scrub) or grass communites. The magnitudes of the differences are not known, but in the case of plantations they will probably be greater the more conditions deviate from those in true, moist, high-forest regions.
>
> 3. The consumption of water by plantations, forests and other plant communities, will depend chiefly on the amount of water available in the soil.
>
> 4. Plant communities of the same ecological order, that is, occupying similar positions in the succession of vegetation, will probably use

approximately equal volumes of water.

5. Swamps and vleis tend to be dried up if trees are planted in them, and <u>also</u> if the natural succession progresses as far as the forest climax. The water is constantly <u>available</u> or accessible to the roots of the trees, because it is stagnant or nearly so.

6. There is no evidence that fast-growing tree species use more water than slow-growing ones - all other factors being equal.

7. The removal of vegetation - natural or artificial - from catchments, especially along stream banks, will cause an increased discharge from streams. The advantage is probably temporary, because it depends on the retention of deep soils rich in humus, which is impossible without a good cover of vegetation."

Australia is well endowed with hardwood forest but is naturally deficient in softwoods. When the Australian Forestry Council was established in 1964, the planting of softwood species was one of the principal topics discussed at its inaugural meeting. The total area of coniferous plantations in Australia at that time was about 650,000 acres. The Council agreed that Australia should aim for an overall planting rate of 75,000 acres per year which would provide a total of 2 million acres and make the country self-sufficient in softwoods by the year 2000.

Much of the area planted will be in the better rainfall areas which also form the water supply catchments for towns and cities. There has been interest by Forestry authorities in the effects that change from native eucalypt to pine species might have on water yields and experiments to study the changes have been established in Queensland, New South Wales and Victoria.

In Queensland, soil moisture measurements are being taken to investigate the nature of water use from Hoop Pine plantations of various ages, from undisturbed rainforest, and from improved pastures. In New South Wales, the Water Research Foundation of Australia financed a joint study by the University of New South Wales and the Forestry Commission, to examine the hydrologic effects of change from native eucalypt to Pinus radiata. This study commenced in 1963. In Victoria, the Soil Conservation Authority has established two experimental catchments of 360 acres and 250 acres at Long Corner Creek to study the influence on water yield of conversion from eucalypt to Pinus species.

The study in New South Wales is the only Australian experiment from which results are available. Eleven catchments, ranging in size from 10 to 760 acres were studied, and an analysis of the data was presented in 1969 by Bell and Gatenby (ref. 40). The results showed no discernible differences between the species and the conclusion was made that "there are other sources of variability between catchments that are more important than mature vegetation." This study is continuing and soil moisture data are now included in the field measurements.

It is of interest to note that the largest water yield in this study occurred from an immature pine cover. This gives support to the thesis that root depth is the dominant factor in water yield, rather than any differences in species of mature forest.

All evidence supports the proposition that there is negligible difference in water yield between species of mature forest. When native eucalypt forest is cleared to establish an exotic pine plantation, there is likely to be an increase in the amount of water yield while the pine forest is immature and has not established its full root depth and this difference should disappear as the trees mature.

4.2.4 Summary of Effects on Water Yield

The forestry practices of clearfelling, thinning, afforestation, and change of species can have an effect on the amount of water yield from a catchment. The most evident effect is when a substantial change in the root depth of the plant cover occurs, as with a change in catchment cover from trees to grass. Change from deep rooting trees to shallow rooting grasses usually results in less utilization of water by the plants and more runoff or groundwater recharge.

When native eucalypt forest is cleared to establish exotic pine plantation, the immature pine forest uses less water and produces more runoff for some years until the trees mature. A similar effect could be expected when a mature pine plantation is clearfelled in a rotation system and replaced with seedlings. There seem to be no detectable differences between mature forests of different species other than those attributable to differences in root depth.

When forests are thinned instead of clearfelled, there appears to be a reduction in water use proportional to the area cleared. It seems probable that there is some critical stand density for each species and age above which no increase in water use would be expected but below which thinning would produce an increase in water yield. However, there is virtually no quantitative evidence on which to justify or evaluate the proposition.

While there have been many studies directed towards interception capacity, infiltration rates, and other components of the hydrological cycle affected by forests (see Part II of this report), there is no discernible pattern in the results available to suggest any general dominant factor other than of difference in root depth.

4.3 EFFECTS ON FLOODS

The effects of forest in delaying and attenuating snowmelt can reduce the peak flows in large rivers where snow melt is the principal flood-producing factor. This may be of significance in the mountain areas of New South Wales, Victoria, and Tasmania. (See section on Snow Management).

There may also be an effect on flood flows from the higher soil moisture levels which occur when the forest cover of a catchment is converted to grass. As described in the section on "Effects on Yield", the replacement of deep-rooting trees with shallow-rooting grass will usually result in less water use and higher soil moisture levels. Reason dictates that this would have an effect in reducing infiltration rates and lowering the abstractions from storm rainfall. It is possible that this could increase some flood peaks, but it seems likely that the effect would be small.

Studies of the differences of interception, infiltration and depression storage capacities of forests and grassland are outlined in Part II of this report. There are no systematic differences in these components of the hydrological cycle from which the different effects on floods of forests and grasslands can be deduced with accuracy.

Early United States studies of the effects of forest cover on floods are listed in bibliographies by Zon (ref. 3) and Munns (ref. 5a). Recent results reported in the literature are conflicting. At the I.A.S.H. Symposium on "Water and Woodlands" in 1959, Anderson and Hobba (ref. 41) reported on comparisons of a 320 square mile catchment with a 665 square mile control, and comparison of a 4840 square mile area with a 320 square mile control in Oregon, U.S.A. Their results from graphical double mass analysis and by multiple regression correlation of flood peaks with meteorological, topographical, geology and cover factors, showed that cutting of forests and forest fires increased flood peaks in both rain-snowmelt floods and snowmelt floods.

By comparison, Johnson (ref. 42) at the Pennsylvania Symposium on forest hydrology, reviewed the available information including the study by Anderson and Hobba and concluded as follows:-

> "Land use significantly affects maximum discharges from small forest and range watersheds. Restoring plant cover on misused land of small watersheds can alter the crests of small peak discharges. Clear-cutting of hardwood forests has not significantly increased streamflow peaks. Clear cutting coniferous forests in the western United States influences storm peaks of snow-fed streams."

Johnson cites studies by Meginnis (ref. 43), Reinhart and Eschner (ref. 44), Ursic and Thames (ref. 45), Packer (refs. 46,47), Goodell (ref. 48), and the TVA (ref. 49) in his review.

There have been a number of attempts to codify the effects of forests on flood runoff into design procedures. The most comprehensive review of these is set out by Storey, Hobba and Rosa (ref. 7). The six methods that they describe are:-

(1) The Infiltration Procedure put forward by Whelan, Miller and Cavallero (ref. 50).

(2) A method of Snowmelt Analysis proposed by Rosa (ref. 51).

(3) Multiple Regression analysis from an example by Anderson (ref. 52).

(4) Regional Analysis from the analysis of effects of fire by Rowe, Countryman and Storey (ref. 53).

(5) Hydrograph Analysis.

(6) U.S. Soil Conservation Service Runoff Curves Procedure.

No detailed use of these methods in Australia is known. Most were derived for U.S. conditions, and all that can be said is that the probable worth for estimating the effects of forests on floods in Australia is very speculative until much testing has been undertaken.

The references already cited in this section include the major reviews, design procedures, etc. which are readily available. Other reports of individual studies are in refs. 54-58.

4.4 EFFECTS ON WATER QUALITY

4.4.1 Introduction

Not all pollution or undesirable substances in water result from human activities. While streamflow from undisturbed forests is generally clear, the water may naturally become turbid during periods of flood flow, or discoloured from decaying vegetation, or even suffer bacteriological contamination from wildlife in the catchment.

Unfortunately the information available on water quality from forested catchments does not cover all relevant problems. In a review of the effects of forest treatment on water quality, Packer (ref. 71) points out that "the most serious shortcoming is that only a few of the watershed-scale studies have had the assessment of water quality effects as a major objective. Most have been concerned with some aspect of water yield, with water quality considerations appearing only as a by-product. Consequently, the quantitative water-quality data from these studies is appallingly meagre in comparison with data on streamflow effects."

The different aspects of water quality that may be affected by forestry operations are:

i. bacteriological quality
ii. turbidity and erosion aspects
iii. chemical quality

4.4.2 Bacteriological Quality

There is very little information available in published form about the effects of forest management on bacteriological quality of water. Teller (ref. 63) reports results from a study of 7 municipal water supply catchments in the Pacific Northwest region of North America. The catchments ranged in size from 51 to 231 sq. miles; average annual rainfall ranged from 50 to 200 inches; and land use varied from water collection only to logging and various forms of recreational use. Coliform concentration was found to increase as runoff decreased in summer months, but the seasonal relationships varied between catchments. Thistlethwayte, in discussion of this paper, presented some data from Australian catchments.

Wild animals can cause bacteriological pollution of water in catchments that are closed to agricultural and similar human activities. This is important where forested catchments in a relatively natural or unmanaged state are used to provide town water supplies. Wild animals can become numerous and, with direct access to rivers and streams, can cause direct fecal contamination of the water.

Walter and Bottman (ref. 59) studied the microbiological and chemical quality of water in an open and a closed catchment, and found the waters of the protected catchment were contaminated by fecal matter from wild animals. Fair and Morrison (ref. 60) investigated the presence of disease producing bacteria, particularly of the genus Salmonella, in a mountain catchment in Colorado. There was one area of concentrated grazing activity by domestic cattle in the lower area of the catchment and large numbers of wild animals, including both small and large mammals, in the less accessible upper catchment. The authors conclude that:-

> "...even supposedly high quality mountain stream water may be a potential source of enteric infection, especially if consumed without treatment. Assumptions by laymen that water, such as has been studied in this investigation, is pure could lead to serious consequences. The isolation of potentially pathogenic bacteria in waters of remote mountain regions clearly substantiated the premise that there is no such thing as a naturally occurring potable surface water. It appears that wild and/or domestic animals are one source of potentially pathogenic enteric bacteria in surface water."

The problems of contamination from wildlife, particularly birds, was noted at the 13th Conference of Authorities controlling water supply and sewerage undertakings in Australia. In discussion of a paper on the multi-purpose use of catchments (ref. 61, p.109), representatives of the Hydro-Electric Commission of Tasmania reported that when humans had been excluded from dams to control pollution, the reservoir area became a sanctuary for birds and resulted in pollution all around the water's edge. Also, from South Australia, it was reported that, when the sewage farm near Adelaide was in operation, seagulls fed at the farm, then flew to the Hope Valley reservoir and washed their feet in the shallows of the reservoir.

4.4.3 <u>Turbidity and Erosion</u>

Turbidity and erosion are considered together in most overseas literature and it is convenient to consider them together here. However, in Australia the problems associated with turbidity have occurred in catchments providing town and city water supplies while erosion problems have lesser importance in this context.

Turbidity has been a source of conflict between forestry and water supply authorities in N.S.W., the A.C.T., and Victoria. Canberra's water supply experienced turbidity problems for many years and this particular example is well documented. In a report on the problem, Teakle (ref. 65) reported:

> "The problem of turbidity in the Cotter Dam developed with time and drew increasing public criticism. The source and cause of the turbidity were a matter of argument, and differences of opinion were well developed by 1931. The question was still unresolved when this brief was accepted in 1962."

In his report to the National Capital Development Commission, Teakle noted that:

> "There is no doubt that the main sources of turbidity are areas of exposed soil - roads, firebreaks, earthworks, newly cleared land, eroded stream banks, etc.."

Soil type and the amount and type of ground cover were identified as the prime factors in determining turbidity. Soils formed on granodiorite and volcanics were stated to be readily dispersible in water and more prone to release turbid water either as surface flow or seepage than soils on other rocks. Snowdon (ref. 68) reports on instruments used for measurement of turbidity in the study. Other reports by the Department of Works (ref. 64), Gilmour (refs. 66, 67), and the A.C.T. Division of the Institute of Foresters (ref. 69) fully describe the problem.

In the U.S.A. Anderson (ref. 70) reported an extensive study of streamflow and sedimentation in 29 forested or partially forested catchments in western Oregon. He related sediment discharge to various catchment characteristics such as erodibility of soils and proportions of the catchment subject to different uses. Anderson found that the most erosive soils and highest sediment-producing soils were developed from intrusive igneous parent rocks, whereas the least erosive soils had developed from alluvium. Packer (ref. 71) reached a similar conclusion with respect to the sediment-producing characteristics of logging roads on various kinds of soils in Montana and northern Idaho.

Dyrness (ref. 72), in a review of the erosion potential of forested catchments, reports that in many areas there is a close correlation between soil parent material and erodibility of the soil. Work in California by Willen (ref.73), Wallis and Willen (ref. 74), and Andre and Anderson (ref. 75) demonstrates that soils derived from acid igneous rocks tend to be considerably more erodible than soils derived from other parent materials. As a result of a study of soils at 258 locations, Wallis and Willen ranked twelve parent materials in the following manner:

Erodible parent materials:

> Granite, quartz diorite, granodiorite,
> Cenozoic non-marine sediments, schist.

Intermediate:

> diorite, a variety of metamorphic rocks.

Non-erodible:

> Cenozoic marine, basalt and gabbro,
> pre-Cenozoic marine sediments,
> peridotite and serpentinite, and andesite.

Wooldridge (ref. 76) also found that soils in central Washington derived from acid igneous rock to be especially erodible.

Fire is a major cause of accelerated erosion from forested catchments, and this subject is dealt with in detail in a following section. Other than fire, there are three principal sources of turbidity and erosion problems associated with forestry practices and activities in Australia. These are:-

a. construction of roads through forests for general access, for fire control purposes, and for the extraction of timber;

b. logging activities, particularly where work is carried out around water courses or where skid tracks are used to haul logs to loading areas;

c. clearing of large areas of native vegetation for the establishment of a plantation forest.

Road construction by necessity involves the removal of plant and litter protection and the exposure of raw mineral soil over a significant portion of a forested area. It is also significant that the cost of road construction in forests is usually a substantial part of the total cost of growing and handling timber to the stage of delivering the log to the mill. Planning of road layouts to minimise erosion and protection of exposed soil surfaces by mulches or seeding is virtually non-existant in Australian forestry practice.

There is very little published information in Australia on the conservation aspects of forest roads, but overseas reports, particularly those by the U.S. Forest Service, offer a good deal of information.

Packer (ref. 71) cites two studies which illustrate the magnitude of the influence of forest roads on turbidity. In 1959, the Pacific Northwest Forest and Range Experiment Station (ref. 78) constructed 1.7 miles of road in a 250 acre watershed on the H.J. Andrews Experimental Forest, baring mineral soil on 6.2% of the area. Maximum streamflow turbidity during the preceding six years never exceeded 200 ppm. During the first rainstorm following road construction, stream turbidity increased to 1780 ppm, while the turbidity in a nearby undisturbed control watershed remained at 22 ppm.

Three experimental drainages in Zena Creek catchment in central Idaho (Copeland, ref. 79), which are situated on highly erodible coarse-textured soils derived from granite, produced sediment yields of 12,400, 8,900 and 89 tons per square mile in the season following construction of jammer logging roads. Watersheds that had no roads yielded no sediment. These high rates of sediment production are attributed not only to the high erosion hazard presented by granite-derived soils, but also to the lack of adequate road drainage facilities.

Methods of controlling erosion from logging roads are discussed by Haupt (ref. 80), Haupt, Rickard and Finn (ref. 81) and the U.S. Forest Service (ref. 78). Papers describing the locating of forest roads to minimise erosion are by Trimble and Sartz (ref. 82) and Packer (ref. 83).

Associated with the problem of roads in forests is that of logging or hauling the log from where it is cut to the point of loading onto trucks for transport to the mill. Roads are generally a few tens of chains apart - values of 500 to 200 feet would be typical. A variety of logging methods are in use and these very widely in the amount of disturbance of the soil.

The worst disturbance is caused by "skid trails" along which logs are hauled on the ground by horses, tractors, winches, etc.. The least disturbance is caused by sky balloons or high-wires which can lift a log clear of the ground for movement.

Packer (ref. 71) has reviewed a number of studies which compare the effects of different logging methods on water quality. Garrison and Rummell (ref. 84) showed that, in ponderosa pine forests of Oregon and Washington states in the

U.S.A., 15% of areas logged by tractors suffered deep disturbance of the soil mantle in the form of skid trails. Cable logging, on the other hand, produced deep disturbance on only 1.9% of the area.

Dyrness (ref. 86) compared soil disturbance and effects on soil porosity of high-lead and tractor logging on the H.J. Andrews Experimental Forest. Forty-one percent of the area logged by a high-lead system was disturbed and this included 9% significantly compacted. Sixty-two percent of the tractor logged area was disturbed of which 27% was seriously compacted. Nearly all of the compaction occurred on skid trails which occupied 28% of the area. Steinbrenner and Gessel (ref. 85) found that tractor skid trails in a similar forest occupied 26% of the logging area.

In the Cascade Mountains of Washington, Wooldridge (ref. 87) compared disturbance of soil created by tractor skidding and a skyline logging. Disturbance from tractors was about 4 times that from the skyline-crane logging. Greatest differences were the areas of deeply disturbed soil. The total area of soil disturbed by tractors in this study agrees closely with values reported by Garrison and Rummell (ref. 84), Fowells and Schubert (ref. 88), and Steinbrenner and Gessel (ref. 85). The area disturbed by the skyline crane agrees closely with values for high-lead logging reported by Dyrness (ref. 86).

Trimble and Weitzman (ref. 89) studied the erosional behaviour of four different kinds of tractor skid trails on the Fernow Experimental Forest. High order skid trails, having gradients of less than 10 per cent and drained by waterbars as needed, produced 55 lb/acre of eroded soil during the first year after logging. In contrast, erosion from poor skid trails having no limit on gradients and no waterbars was almost eight times as great - some 433 lb/acre.

Measurements of logging disturbance and of soil eroded from skid trails are not necessarily a measure of damage to the quality of streamflow. Some of the eroded soil may be filtered out by lesser vegetation and litter may not reach streams. Such measurements, however, are indicative of potential damage to water quality where skid trails concentrate water, intersect other skid trails or roads, and encroach on stream channels.

In Australia, logging is done by contract rather than by day labour, and supervision for conservation or catchment management is left for the district forester in each case to work out with each contractor.

Since the beginning of the accelerated programme of establishing softwood plantations in Australia, clearing and planting of areas as large as 1500 acres in one operation has occurred. The clearing and planting has a number of phases in which the turbidity in runoff water can be seriously increased.

First, one method of removing the native vegetation is to bulldoze all cleared material into windrows about 300 feet apart for burning; then plough the area between them to prevent natural regrowth. Windrowing and ploughing in straight lines across country is more common than around contours. The practice offers substantial opportunities for turbidity and erosion problems to arise.

Second, there is a period of two to four years from the planting of seedlings to when the new forest can offer adequate protection to the soil. A large storm created considerable problems of turbidity in the Shoalhaven River in New South Wales which provides Nowra's water supply, during such an interval after the establishment of a softwood plantation near Mongarlowe.

Third, clearfelling a plantation forest and replanting for a new crop in a rotation system will mean substantial disturbance of the ground at intervals of 20 - 40 years. The programme of softwood planting in Australia will eventually reach a stage where 75,000 acres will be clear-felled and replanted each year.

The problems of road construction, logging and clearing for the establishment of softwood plantations are of most concern for management of forests in water supply catchments. However, there is very little published information about these problems in the Australian environment. While it is fair to record that a start has been made to collect some water quality data in Queensland, New South Wales, and Victoria, to study the effects of forestry practices on turbidity and erosion, little information of practical use is currently available.

4.4.4 Chemical Quality

In areas of high rainfall and little destruction of forest litter by fires, decaying vegetation can contaminate water supplies in a number of ways. The oxygen demand of the decaying vegetation can deplete the dissolved oxygen in the water and kill fish and other aquatic life. Serious taste and colour problems can be caused which may necessitate treatment of the water if it is used for town supplies. Also the acidity can be raised sufficiently to cause problems for some industrial uses.

The rivers of southern Tasmania are affected in this way, but there is little published information available. A report by Feltz and Slack (ref. 62) in the U.S.A. gives a description of the problem as it occurs in the North Fork of the Quantico Creek near Washington, D.C.

A problem of more recent origin is the effect on water quality of spraying forests with insecticides. Elson and Kerswill (refs. 90-92) give an extensive description of the effects on salmon of DDT spraying on New Brunswick's forests. In addition to the immediate killing of young fish which resulted, there was evidence of delayed mortality that occurred 4 to 6 months after spraying. Cole et al (ref. 93) made a comparison of DDT levels in fish, streams, stream sediments, and soil before and after an aerial spray application in northern Pennsylvania. Graham (ref. 94) reports on the effects of forest insect spraying on trout and aquatic insects in streams in Montana.

However, two studies have shown no contamination of water supplies when herbicides have been used on forests. Reigner, Sopper and Johnson (ref. 95) studied the extent of streamflow contamination by herbicides when vegetation along the stream channels of two small forested watersheds was sprayed with 2,4,5-T by means of a mistblower. Water samples were taken just above and below the treatment area and one mile downstream immediately after spraying, 4 hours later, and for several days thereafter. Contamination was found in samples taken within 4 hours of treatment just below the treated area and later after a 1-inch rain. There was no contamination one mile down stream.

Reinhart (ref. 96) studied the use of herbicides to increase water yield. Before clearcutting a portion of an experimental watershed on the Fernow Experimental Forest during the winter of 1963, all trees above 1 inch d.b.h. were basal sprayed with 2,4,5-T in No. 2 diesel oil. After cutting sawlogs and pulpwood, all stumps were sprayed with the same mixture. In the following May and June the foliage of residual vegetation was sprayed with 2,4,5-T with knapsack mistblower. During these treatments numerous water samples were obtained from the stream immediately below the treatment area and sniff-tested. There was no evidence of contamination by the herbicide.

4.5 EFFECTS OF FIRE

4.5.1 Introduction

Forest fires are of two main types - uncontrolled (or wild fires), and controlled (or prescribed burning). The latter type of fires are deliberately lit, being low intensity fires started in periods of low bushfire danger and in such a manner as to prevent spread. They are designed to remove fuel from the forest floor and so lessen the chances of wild fires in summer periods. Burning of pastures by graziers in order to promote a flush of winter or spring growth is another form of deliberate fire but not related to forestry.

The hydrologic effects produced by fire in a catchment vary greatly according to the type and condition of the soil, vegetation, litter cover, and topography as well as on the characteristics of the fire itself. It is beyond doubt that intensive burning increases erosion, and many studies suggest increased runoff as well. The difficulty is that few if any studies provide information or data that can be extrapolated to other situations and/or other areas.

It may be noted at this point that the amount of runoff and erosion following any burning also depends on the timing and pattern of rainfall which follows. Light showers at regular intervals following an extensive burn can promote rapid regrowth and result in little or no runoff or erosion. Few studies attempt to provide the detailed information that could account for such circumstances in quantitative terms. However, numerous qualitative studies have been made and their results offer some guidelines if not complete answers.

4.5.2 General Review

Two major reviews of the ecological effects of fires have been prepared, one by Shantz (ref. 132) and the other by Ahlgren and Ahlgren (ref. 98). Both reviews consider the hydrologic effects of fire as part of the overall effects produced. Cushwa (ref. 108) has prepared a summary of literature on fire in the United States from the mid-1920's to 1966. In Australia, Cooper (ref. 107) has prepared an annotated bibliography of the effects of fire on Australian vegetation.

Ahlgren and Ahlgren (ref. 98) cite many studies that have reported increased erosion rates due to fire. Elwell et al (ref. 110) reported that, over a nine year period, water soil losses were 12 to 31 times as great on burnt as on unburnt woodlots. Haig (ref. 114) reported that runoff was 31 to 463 times as great and erosion was 2 to 239 times as great in burnt areas in pine forests. Other studies reporting increased erosion are listed in the bibliography, (refs. 104, 106, 109, 112, 115, 128 and 129). Biswell and Schultz (ref. 103) report no effect on runoff and erosion following prescribed burning.

One of the earliest and best reported studies of the effect of fire on runoff and erosion is that by Hoyt and Troxell in 1932 (ref. 116). The report describes the 6.5 sq. mile Fish Creek catchment in Southern California where the U.S. Geological Survey had good streamflow records before and after a severe fire on 31 August 1924. The fire completely stripped the catchment of all plant life and tree litter.

Hoyt and Troxell used the neighbouring Santa Anita Creek catchment as a control and established a relationship between the two streamflow records. The comparison showed an increase of approximately 30% in average annual yield due to the fire and substantial increases in peak rates of runoff on the burnt catchment for the first year after the fire.

Other studies in California have shown considerable variation in results. Rowe (ref. 130) reported substantial increases in both runoff and soil loss from burnt North Fork plots compared to unburnt controls. By contrast Veihmeyer and Johnston (ref. 135) from 42 trials in burning grass and brush concluded that runoff and soil loss had not been accelerated by annual burning, nor had infiltration been influenced.

In 1947, Adams, Ewing and Huberty (ref. 97) reviewed the literature on brush burning in California but, because of the studies cited above, were unable to come to any conclusions concerning the relationships of burning and floods. Later, Anderson (ref. 99) claimed that consideration should have been given to differences in natural cover. By re-arranging the data of Veihmeyer and Johnston, he demonstrated that burning increased both runoff and erosion.

4.5.3 <u>Study by Rowe, Countryman and Storey</u>

The most comprehensive design procedure for evaluating the effects of fire on runoff and erosion has been developed by Rowe, Countryman and Storey (ref. 53) and this has been described and set out by Storey, Hobba and Rosa (ref. 7). The analysis by the former mentioned group of authors was made to determine the effects of fire on storm runoff and erosion in Southern California.

(a) Determining Effect of Fire on Peak Discharge

The method used to determine the effect of fire on peak discharge was to group watersheds into storm zones and to select a key watershed in each zone. A long record of precipitation and streamflow and a long unburnt condition were essential requirements in selecting key watersheds.

A frequency distribution of peak discharge rates was made on those watersheds with adequate records. The effect of complete burning of watershed cover was then determined by:-

(i) comparing peak discharge rates of burnt watersheds with those of similar but unburnt watersheds for the same storm;

and (ii) comparing peak discharge rates from similar storms on the same watershed before and after burning.

Watersheds used in the determination were restricted to those in which measurements of streamflow were available for the burnt and comparable unburnt watersheds, and in which the normal vegetative cover consisted of chaparral associations of average density.

The comparisons were made storm by storm by years after the last fire. Similarity of watersheds was judged by comparison of frequency-discharge curves and watershed characteristics. The most probable size of each peak discharge event of the burnt watershed, had the area remained unburnt, was first determined. The frequency of each discharge peak from the unburnt watershed was assumed to be the same as the frequency of the corresponding peak from the key and other nearby unburnt watersheds.

Using this frequency, an estimated peak for the burnt area in an unburnt condition was read from its normal frequency curve. The ratio of the observed peak of the burnt watershed to the computed peak for unburnt conditions was then calculated to obtain the "fire-effect ratio". Similar ratios were developed by comparing peak discharges occurring from watersheds before complete burning with those occurring in the same watersheds after burning. The ratios were plotted over their corresponding frequencies on logarithmic paper for all years after burn for which data were adequate. Variations were eliminated by fitting smooth curves through the plotted points.

(b) Determining Effect on Erosion Rates

Data used in determining rates of normal erosion consisted of measurements of siltation in reservoirs situated in watersheds with normal vegetation cover. Because of the short length of the records available, it was necessary to determine relations between the recorded peak discharges and erosion rates. The first step in doing this was to prorate measured erosion to the individual discharges that produced it.

A representative cross section of the stream channel just upstream from the reserve was selected for determining velocities by peak discharge sizes. The shape, cross-sectional dimensions, and an average slope of this section were determined and a roughness coefficient was assumed. Using the Kutter formula, a series of velocities was computed for various depths.

A velocity-flow graph was then plotted showing velocity in feet per second by flow in cusecs. Velocities for all discharge peaks during the period of siltation measurements were determined from this graph and the total eroded material was distributed to individual peak discharges in proportion to the fifth power of the velocity. This provided the relation between erosion rate and peak discharge. The relationships from five catchments showed little variation so all were combined to form a single relationship.

Determination of the effect of fire upon erosion was based on comparison of erosion rates of completely burnt watersheds with those of unburnt watersheds. Ratios of erosion from the burnt watersheds to erosion for corresponding periods from the key watershed were first computed and these became practicably constant in 9 to 10 years indicating the establishment of relatively stable conditions and normal erosion rates.

Using these ratios, estimates were made of the most probable rates of erosion if the key watershed were burnt. The calculated figures were plotted and smooth curves fitted through the plotted points to give average relations between normal peak discharge and erosion by years after burning.

4.5.4 Australian Studies

In Australia, McArthur (ref. 124) has reported increases in streamflow following fires on catchments in both Victoria and Western Australia (see Tables 1 and 2). Table 1 shows the effect of fire on streamflow in the Bogong High Plains of Victoria, and Table 2 shows the effects on three catchments in Western Australia.

Table 1

The Effect of Fire on Streamflow - From Sub-Alpine Vegetation in the Bogong High Plains of Victoria January, 1939

Date January	Rain (pts.)	Streamflow (Cusecs) Burnt	Streamflow (Cusecs) Unburnt	Increased Streamflow (Cusecs)
5	-	14	17	
7	-	13	17	
9	5	12	15	
10	-	12	13	
11	-	9	12	Fire Occurred
12	-	14	11	5
13	-	16	11	7
14	-	17	11	8
15	-	17	12	7
16	59	29	21	12
17	112	42	32	16
18	8	35	22	17
19	-	28	21	11

Table 2

The Effect of Fire on Streamflow in Jarrah (E. marginata) Forests Near Dwellingup, Western Australia, January, 1961

Date January	STREAMFLOW IN CUSECS North Dandalup	South Dandalup	Davies Brook
17	0.1	1.2	0.6
18	0.1	1.2	0.5
19	No Flow	1.2	0.35
20	No Flow*	1.2	0.5
21	0.7	1.2	0.6
22	0.2	1.2	0.6
23	0.3	1.2	0.6
24	0.5	1.0*	0.6*
25	0.9	1.5	0.7
26	1.7	2.3	1.1

* The catchment was burnt on this day

McArthur and Cheney (ref. 11) report increases in annual streamflow, ranging from 43% to 235%, due to fire in the Cotter River catchment which provides Canberra's water supply. The data reported are given in Table 3.

Table 3

Increased Streamflow following widespread fires in the Cotter catchment (1911-1962)

Year	Calculated flow from monthly rainfall (acre feet)	Actual Flow (acre feet)	Percentage Increase
1917	146,000	260,000	78
1918	40,000	134,000	235
1923	64,000	133,000	108
1926	56,000	157,000	180
1939	115,000	164,000	43

Pereira (ref. 24) reports some data from the Snowy Mountains Hydro-Electric Authority on increases in streamflow and erosion due to fire. A major uncontrollable fire in inaccessible country in the Australian Alps burnt out the catchment areas of the Wallace's Creek and Yarrangobilly River, of 16.8 and 87.5 sq. miles respectively. These catchments had been gauged for eight years before the fire with detailed sediment sampling.

The flow pattern deteriorated abruptly with sharp peaks from the burnt out areas. Rainstorms which from previous records would have been expected to give rise to flows of 200-300 cusecs produced a peak of 1300 cusecs. The sediment load at a flow of 100 cusecs had been increased by 100 times compared with the load before the fire.

A storm occurring some 7 months after the fire gave the highest sediment concentration recorded at Wallace's Creek. At a flow of 334 cusecs, the concentration was 14.4% by weight, equivalent to 115,000 tons per day. On the same day the Yarrangobilly River with a flow of 166 cusecs yielded an equivalent sediment load of 45,000 tons per day. The Snowy Mountains Hydro-Electric Authority estimates from the increased flow rate and increased sediment concentration that the total sediment load in Wallace's Creek is probably one thousand times greater than it was before the fire.

By contrast, no erosion or increase in turbidity was experienced in the Chichester catchment providing Newcastle's water supply following the severe fire in November, 1968 which burnt about 20% of the catchment in the region immediately around the dam. No heavy rain was experienced for over 6 months following the fire and there was opportunity for ground vegetation to become re-established without erosion or severe floods occurring. This illustrates the importance of climatic pattern in the period immediately after a fire as another factor to consider in estimating the effects of a severe burn.

4.5.5 Summary

The only information which has been codified into a useable design procedure for evaluating the hydrologic effects of fire is that prepared by Rowe, Countryman and Storey. This cannot be recommended for immediate use in Australia because of the numerous assumptions made in the analysis which appear somewhat arbitrary.

However, the method certainly warrants further study and it is recommended that the original report, rather than the rewritten material in ref. 7, be obtained when further experiments on this subject are planned in Australia.

In summary, no single statement can be made to simplify the complex relationships among the characteristics of the fire, the site and the climatic pattern after the burn, in determining how fire will affect the quantity or quality of water resources. There is need for more study of erosion processes on uncovered ground and more study of the patterns of intense rain which are the principal causes of damage after fire.

It seems clear that prescribed burning of low intensity at pre-determined times offers a low risk of adverse effects on water resources compared with the uncertain risk of high intensity wildfires if fuel is allowed to accumulate on a catchment. There is considerable opportunity here for management to influence the effects that fire will have on water supplies.

4.6 SNOW MANAGEMENT

In alpine areas, forests can act to modify the natural patterns of snowfall and snowmelt in two ways. By altering the aerodynamic characteristics of the ground surface the locations and amounts of snow deposition can be be affected. By absorbing incoming radiation that would otherwise be reflected back into space from an exposed snowpack, the pattern of snowmelt can be affected.

Generally the objectives of watershed management in snow-fed catchments are two-fold. Where water supplies are deficient, a principal objective will be to increase total water yield. Where supplies are adequate, an objective will be to attenuate the period of snowmelt to lessen flooding and aid the regulation of the river flow.

Observations of the effects of forest layout on snowcatch date back to 1912 (ref. 137). Connaughton (ref. 138) in 1935 reported on the effects of vegetation on the accumulation and rate of melting of snow. More recent reviews of the possibilities of managing snowpacks in forested catchments have been put forward by Martinelli (refs. 139-143), Goodell (ref. 48), Anderson, Rice and West (ref. 144), Kittredge (ref. 145), Goodell and Wilm (ref. 146) and Hoover and Leaf (ref. 147). Costin (ref. 148) has investigated the possibilities for manipulating snow by forest management in the alpine areas of Australia.

A more detailed discussion has been made in Part II of the report, dealing with the influence of land use on components of the hydrological cycle. Generally, the results of the studies cited may be summarised as follows:-

(1) More snow accumulates in small openings in forests than under trees. Small openings accumulate more than large openings, the optimum size of opening being about 4 to 10 times the height of surrounding trees.

(2) On small catchments, the extra snow accumulated in openings in a forest may be a true increase in snow catch. On large catchments, it seems more likely that the difference in snowfall between openings and under trees is more a redistribution of the snow, rather than any overall increase in amount falling on the catchment.

(3) Redistribution of snow into deeper falls over small areas may be of some benefit in attenuating the runoff from melting of the snow.

4.7 SUMMARY OF THE EFFECTS OF FORESTS

4.7.1 Effects on Yield

There is considerable evidence to show that trees use more water than grass and that more runoff or groundwater recharge could be expected when a tree covered catchment is converted to a grass cover. It must be emphasised that the differences in water yield will be small and may be insignificant in relation to the very large natural variability of the flow in many Australian rivers.

All studies which have been made to compare the water use of hardwood and softwood tree species have not delineated any differences in water use other than could be attributed to differences in root depth. It appears that mature forests of different species under the same conditions generally use about the same amounts of water.

Studies of the differences in interception, infiltration, and depression storage capacities between trees and grass covered areas do not show any systematic effects on water yield of the same magnitude as that caused by difference in root depth.

4.7.2 Effects on Floods

When a forest is substantially defoliated and the ground litter removed by fire, there is sufficient evidence to show that flood flows are higher than would be expected if the forest had been undisturbed. However, the comparisons of floods from forested and grass covered catchments is not so clearcut, and any increase in floods from grassed areas compared to forests appears to be small.

The erosion control benefits of a forest cover are universally accepted by authorities controlling catchments, but the reduction in flood peaks by forests compared to grass and bare soil is of much smaller significance in practice.

4.7.3 Effects on Water Quality

Three major forestry practices are significant in affecting water quality - the construction of access roads, logging, and clearing for establishment of softwood plantations. In the eastern states of Australia, the practices are widely associated with problems of raising turbidity levels in water supplies and to a lesser extent, promoting erosion. In Western Australia, clearing causes problems of salting in areas of shallow saline groundwaters and salt is a dominant factor restricting the permitted degree of logging and clearing.

In North America, some study has been made of the residues of pesticides in streamflow following aerial spraying of insecticides over forests or use of herbicides along stream banks. These problems do not appear to have arisen yet in Australia.

4.7.4 Effects of Fire

There is substantial evidence to show that sediment production can be very high when a heavy storm occurs after fire has burned a forested catchment. There is also some evidence that flood flows can be increased in the same manner. However, both effects depend on climatic pattern. Where light rain follows at regular intervals after a fire, regrowth can be rapid and no effect on flood peaks or erosion may occur.

American experience, particularly that from California, has been codified into graphs for estimating increases in both flow rates and sediment production in the years following bad fires. This information, while useful for estimating possible magnitude of the effects involved, could not be recommended for use in Australia until substantial testing has been undertaken.

4.7.5 Snow Management

Overseas studies of the management of forests for manipulating snow accumulation and snow melt on catchments in alpine areas appears not to have progressed much beyond the stage reached in Australia.

There is evidence that openings in forests can be used to increase the deposition of snow. It appears that this occurs at the expense of snowfall on other areas, the effect being a redistribution rather than any overall increase over large areas. The effect may be useful in attenuating snowmelt to aid in regulation of flow, but studies to date are inadequate for establishing operational procedures.

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CHAPTER 5

ENGINEERING WORKS

5.1 INTRODUCTION

In this project, the prime concern is that of rural land use, and little attention has been given to wholly urban aspects, such as flood flows in built-up areas, pollution from sewage disposal, industrial wastes, and similar non-rural aspects. However, there are some engineering works associated with rural land use that are relevant to the project.

Dams and reservoirs which provide rural water supplies range in size from stock ponds of a few thousand gallons capacity up to major reservoirs used to regulate river flows and divert waters for irrigation of large areas. In the U.S.A. flood detention dams, distinct from storage reservoirs, are commonly incorporated into conservation flood control programmes.

Modern expressways provide large impervious surfaces which can increase the amounts and rates of runoff in localised areas. This effect of increased runoff from road surfaces has been deliberately utilised in the drier areas of Australia by the construction of "roaded" catchments and similar surfaces to increase the natural amount of surface runoff.

The change from rural land use to urban use as the fringes of cities expand into the countryside is one aspect that has received some attention overseas, particularly in the U.S.A. The information available from these studies is of some help in studies of the hydrology of rural land use.

One type of engineering activity occurring in rural areas of Australia that has considerable impact on water quality is mining. A short review of the problems encountered in Australia and the information available is made in the following sections.

Finally, a brief review is made of the problem of thermal pollution caused by the waste heat from power stations being "dumped" into a river or stream when the water is used for cooling purposes.

5.2 DAMS

The dams associated with conservation programmes and agricultural development are of two types - storage dams which are allowed to fill to provide water for use, and flood detention dams which fill during floods and are then emptied over a period of a few weeks at controlled rates.

The storage dams encountered in rural areas of Australia range in size from small stock ponds to major reservoirs. There are large numbers of farm dams on individual properties and, generally, numbers of dams of a given size decrease as the size increases.

There have been some surveys made of the numbers of farm dams in four states of Australia. de Laine and Vasey (ref. 1) surveyed numbers and sizes of these dams in central districts of Victoria; Boughton and Burton (ref. 2) report results of a survey in New South Wales; Rawlings (ref. 4) studied farm dams in the Brigalow areas of Queensland; and McKenry (ref. 3) reports a survey of farm dams in Western Australia. In the U.S.A., Gambell (ref. 5) estimates that there are two million farm ponds which supplement the major water resources of the nation.

The effects of such large numbers of small storages on the amounts and rates of runoff are not fully established. In drier areas, it is axiomatic that runoff will be reduced because of the abstractions and use of water from the storages. But studies of the effects have been few.

Nelson (ref. 6) cites a study by Carothers and Newman (ref. 7) of the effects of stock ponds on water yield of the 13,000 sq. mile Brazos River catchment in an area of 20-30 inch rainfall. It was estimated that the 18,000 ponds in the catchment, each controlling an area of 25 acres, would reduce the average annual runoff by about 1.7%.

Sharp, Gibbs and Owen (ref. 8) developed a procedure for estimating the loss by evaporation and seepage from farm dams over a large catchment and the effect of these factors on annual runoff. Culler and Peterson (refs. 9, 10) have estimated the effect of stock reservoirs on runoff in the Cheyenne River basin in the U.S.A.

More attention has been given to the effects of these ponds on reducing flood peaks than on volume of runoff. Zingg (ref. 11) evaluated the costs and flood control benefits of farm ponds averaging 2.3 acre feet capacity. He concluded that ponds kept empty as flood retarding structures could recover only 40% of their cost in saving flood damages while ponds allowed to fill for other uses would recover only 8%.

Floodwater retarding structures or detention dams are not common in Australia but they are the primary means of reducing flood peaks in conservation programmes of the U.S. Soil Conservation Service. The dams in these U.S. programmes are generally much larger than the farm dams which are common in Australia. Francis (ref. 13) gives a description, based on averages of 2,500 dams in small watershed projects, which illustrate the size of structure involved. Earth fill averages 80,000 cubic yards with costs (in 1963) averaging $50,000; flood pool capacities average 900 acre feet.

Hartman et al (ref. 12) describe the use of flood detention reservoirs in a 250 square mile tributary of the Washita River in Oklahoma. Each of the 25 reservoirs that were completed in 1962-1963 had a storage capacity equivalent to $3\frac{1}{2}$ inches of runoff from its own catchment. Eighteen more such reservoirs were planned as part of the overall project in this catchment.

The relative merits in flood control of large numbers of medium size dams such as these on tributaries versus one large dam on the main river has been a source of controversy in the U.S.A. Leopold and Maddocks (ref. 14) have reviewed the problem in admirable detail and have compared the merits of each approach. Generally, the effect of flood control dams is to reduce floods in the valley immediately downstream of the storage but the effect diminishes considerably with distance downstream. Leopold and Maddocks give values to illustrate the different flood reductions obtained from one main stream dam with a catchment of 600 sq. miles and from a number of smaller dams each controlling 10 sq. miles of tributaries as an alternative.

Major reservoirs can have a significant effect on the quality of water entering the storages. Symonds et al (ref. 15) have prepared a comprehensive review of literature on this subject and have set out a list of research needs.

5.3 ROADS

There are two aspects of roads which are important in catchment management in Australia - erosion from the areas of soil exposed in construction, and the use of roaded catchments for increasing water supplies in the drier areas of the continent.

The problem of erosion from forest roads, constructed for fire access or for logging, has already been discussed in the chapter on Forests. Forest roads are rarely sealed and the exposed surfaces in cuttings and drains, as well as the pavement, provide sources of sediment and turbidity. Controlling erosion and turbidity from the construction of forest roads is one of the prime problems in catchment management.

But the problem is not wholly associated with forests. Harris (ref. 16) and Skurlow (ref. 17) describe the problems of erosion encountered with road drains in New South Wales. Weigle (ref. 18) describes the problem of erosion from abandoned coal-haul roads. Diseker and Richardson (refs. 19, 20) report on sediment production from highway cuttings, and the control measures used. Vice, Ferguson and Guy (ref. 21) describe erosion which occurs in suburban highway construction. The report by Wolman and Schick (ref. 46) gives data on measured areas of exposed soil and rates of sediment production from roads in urban areas of Maryland, U.S.A.

But the effect of roads on runoff, which is of most importance in Australia, is the increased yield which occurs from the compacted and/or paved surfaces of roads. In areas where natural runoff is inadequate to meet needs, the surfaces of catchments have been treated to increase water yield by several means - by shaping and compacting the surface in the same way as for road formation; by bitumen paving the ground surface; and by covering the ground surface with sheet iron.

"Roaded catchments" were developed by the Public Works Department of Western Australia (ref. 22) and have been used on the Eyre Peninsula, in South Australia (ref. 23) and in Queensland. Construction involves the clearing of all vegetation from the catchment, shaping and smoothing the land surface to lead runoff into collecting drains, and then compacting the soil to increase water yield. Operational problems which include weed control and fencing to exclude stock from the area, are also problems with bitumen covered areas, and iron-clad catchments to a lesser extent.

Recently, more attention has been given to bituminous surfaces in place of the "roaded" catchment. Kelsall (ref. 24) describes the method of construction of these used in Western Australia, and experiments in the performance of these surfaces have been carried out at the University of New South Wales. In the U.S.A., Myers (refs. 25, 26, 30) and others (ref. 27-29) have developed sprayed asphalt-soil pavements for water harvesting. The paper by Myers, Frazier and Griggs (ref. 27) gives a good description of the asphalt materials used, construction methods, and field tests of pavement performance. Chinn (ref. 29) describes a 16,940 square foot asphalt catchment built in Hawaii in 1958 which deteriorated rapidly by cracking and by growth of vegetation through the paved surface.

Myers and Frazier (ref. 28) have made both laboratory and field tests of chemicals which make soil water-repellant. They review the available information on hydrophobic soils and materials, and report the results of tests on five types of chemicals. A 50 ft. x 50 ft. plot, treated with sodium methyl silanolate compound which costs about U.S.$250 per acre, produced 94% runoff from 9½ inches of rain in a five month period following the treatment.

The most artificial type of catchment used in Australia is the iron-clad area covered with sheet iron. One catchment at Nowingi, about 30 miles south east of Mildura, has been in use for about 30-40 years. Others have recently (1965) been constructed by the Irrigation and Water Supply Commission in Queensland, one at the Moura research station and two on private farms. Costs equivalent to 1970 prices would be about $8,000 per acre.

5.4 CHANGE FROM RURAL TO URBAN LAND USE

5.4.1 Introduction

The widespread trend towards more urban development is expected to continue in Australia for some time to come. The expansion of the major cities into the countryside results in a rural-urban contact zone around the periphery of development in each case. It is beyond the scope of this project to fully delve into the hydrology of urban areas, but it is relevant to consider the changes which occur as land use changes from predominantly rural to predominantly urban.

Jens and McPherson (ref. 31) give a review of the major aspect of urban hydrology. The principal problems generally encountered are three-fold:-

(i) The demand for water is usually very high and concentrated in an area too small to supply needs. Catchments usually extend well outside the boundaries of development and water must often be brought over large distances.

(ii) Storm runoff from roads, houses, airports, etc. is high while at the same time development often encroaches onto flood plains of the natural drainage system. Management of flood waters becomes difficult.

(iii) Domestic waste waters and industrial wastes produce major problems of disposal as the concentrations of population increase.

Savini and Kammerer (ref. 32) have reported on a review, classification, and preliminary evaluation of the effects of urbanization of the hydrologic regime. They trace a hypothetical change in land use from pre-urban to early-urban, middle-urban and late-urban stages with an outline of the possible hydrologic effect of activities in each stage, e.g. removal of trees, paving of streets, restriction of watercourses to artificial channels and tunnels, etc.

Two major aspects of urban development have been the subjects of a significant number of reports in the literature - the effect of urban development on flood discharges, and the increases in sediment and turbidity due to urban construction and building. Only a little attention has been paid to the increase in water yield as rural land changes to urban areas although it is certain that some increase occurs. The other aspect of importance, i.e. the disposal of urban waste water, constitutes a subject much bigger than this project can adequately deal with, and is not considered here.

5.4.2 Effects on Yield

Sawyer (ref. 33) reports one of the few studies where volume of flow has been considered instead of flood peaks. A comparison was made of two catchments, $11\frac{1}{2}$ and 31 square miles in area, in Long Island, New York, when the large catchment was affected by urban development. A comparison of concurrent streamflow records for Mill Neck Creek (11.5 square miles) and East Meadow Brook (31 square miles) in Long Island, New York, showed that a definite change in runoff relations occurred with the urbanization of East Meadow Brook.

A comparison of precipitation and average total, direct and base runoff for both streams for the periods 1938-51 unurbanized; and 1952-62 urbanized; gives the following: at Mill Neck Creek, the increases in percentage of total runoff, direct runoff, and base runoff are similar, ranging from 6.1% to 7.3%, and are closely comparable to the 9.4% increase in precipitation. At East Meadow Brook, on the other hand, total runoff increased 1.15 inches, or 15.8%; direct runoff increased 0.80 inches, or 123.1%; base runoff increased 0.35 inches, or only 5.3%. Comparison in annual peak discharge shows a marked increase with urbanization.

Stall and Smith (ref. 34) also give some information on the effects of urbanization in yield. This study compares a 4.6 square mile watershed containing five rain gauges and a 12.3 square mile rural watershed containing one rain gauge. The eleven year records are compared by mass curves of runoff, flow duration curves and unit hydrographs from one storm. Reactions of the basins to periods of drought as well as storms are considered.

Harris and Rantz (ref. 35) report results from a study of a five square mile catchment in California where the impervious area increased from 4% to 19% over a 13 year period. The report contains an analysis of rainfall and runoff volume records and double-mass curve comparison of the study area with an index area. Espey and others (ref. 36) used linear regression analysis for study of data from 24 urban and 11 rural catchments in Texas and found more runoff from the urban areas.

Muller (ref. 37) sets out a water balance method of estimating the effects of urbanization on water yield, using Thornthwaite's approach to moisture storage capacities and evapotranspiration loss.

5.4.3 Effects on Floods

A Task Force on Effect of Urban Development on Flood Discharge, appointed by the Committee on Flood Control of the American Society of Civil Engineers (ref. 38) has surveyed current knowledge and prepared an annotated bibliography of 68 references. Their review points to three phases being important in the effect of urbanization on floods:-

(i) Impervious areas increase the natural rate of surface runoff.

(ii) Gutters and stormwater drains carry flows at much higher velocities than natural water courses.

(iii) Natural stream channel capacities can be reduced by flood plain development, enclosure of flow in stormwater drains, and aggradation of the channels by increased sediment from the construction phase of urban development.

Watkins (ref. 39) describes a study of the effects of urbanization on a 5270 acre catchment near Harlow New Town in England. Wilson (ref. 40) reports on a preliminary analysis of streams draining the city of Jackson in Mississippi. It was found that increases in flood peaks ranged from 200% to 300% depending on the degree of development and the magnitude of the flood, and that the degree of the effect decreases with increasing flood magnitude.

Espey, Morgan and Masch (ref. 36) used linear regression analysis to compare data from 24 urban and 11 rural catchments in Texas. The results showed that urbanization leads to higher peak flows occurring in shorter time intervals.

There have also been studies of how urbanization changes the characteristics of the unit hydrograph of a catchment. Crippen (ref. 41) presents unit hydrographs representing conditions before and after suburban development for Sharon Creek in California. Van Sickle (ref. 43) reports on changes in unit hydrograph characteristics for a 90 square mile catchment near Houston, Texas, which changed from agricultural to urban land use after World War II. Wiitala (ref. 42) found that the lag times of a 36.5 square mile urban watershed and a 22.9 square mile rural watershed were about three hours and twelve hours respectively, while the urban flood peaks were about three times those of the rural area.

More recently, attention has been given to the use of mathematical catchment models for simulation of changes in the hydrologic regime as a rural area changes to an urban cover. James (ref. 44) used the Stanford Watershed Model and varied the model parameters to simulate the effects of urban development and channel improvement on a digital computer. Narayana and Riley (ref. 45), by contrast, used an electronic analogue computer to simulate similar changes on a four square mile catchment at Austin, Texas, for study of changes in peak rates of flow, rise times, total volume of runoff, and duration of flow.

5.4.4 Effects on Sediment Production

Wolman and Schick (ref. 46) have made a detailed examination of how construction activities in urban and suburban areas of Maryland, U.S.A., affect the production of sediment. These authors estimated that, in four counties adjacent to Baltimore and Washington, about 7.2 square miles of land are cleared for construction at any one time. Housing and other buildings accounted for 5.7 square miles and highways for 1.5 square miles. Sediment yields from construction areas ranged up to 140,000 tons/square mile/year compared with up to 1000 tons/square mile/year from agricultural areas and 200-500 tons/square mile/year from forested catchments.

Guy and Ferguson (ref. 47) describe how expanding urban areas can cause serious sediment deposition in small reservoirs. They cite an example of Lake Barcroft near Washington where 19 acre-feet of sediment have been deposited for each square mile of completed residential construction.

A review of existing knowledge of sedimentation in urban environments has been prepared by Dawdy (ref. 48) and a statement of research needs by Guy (ref. 49). Other studies have been reported by Anderson and McCall (ref. 50), Dumper (ref. 51) and Barnes (ref. 52).

5.5 MINING

Mining may be considered to be a "rural" land use for the purpose of this project because it is primarily associated with rural rather than urban areas. The pollution of water supplies by mining activities is part of the overall water quality problem and is considered here for completeness.

Water pollution arises from mining activities in the following ways:-

a. Pumping of water from mines;

b. percolation of water through spoil dumps;

c. erosion of spoil dumps;

d. discharge of effluent from coal washing plants;

e. sluicing.

Coal mining is usually more troublesome than other forms of mining and is more widespread. Water which has been in contact with coal strata commonly contains free sulphuric acid and other components which react to form acid. pH values of three or less would be typical. The acid creates an environment which is generally incompatible with aquatic life, recreational use, rural requirements for stock or irrigation water, or industrial use.

However, the most well-known instance of pollution from mining activities is the now-abandoned copper-lead-zinc mine at Captain's Flat in the headwaters of the Molongolo River about 30 miles upstream from Canberra. Mining dates from 1882 but the main activities and major pollution were in the period 1938-1962. Collapses of slime dumps deposited fine tailings in the river, and these can still be detected far downstream along 30 to 40 miles of the Molongolo. Although the mine is now closed, leaching of spoil banks still causes zinc pollution immediately at the site of the works, and the effect diminishes downstream. A detailed description of this problem has been reported by Weatherley, Beever and Lake (ref. 53) and by Haldane (ref. 54).

A major review of water pollution in Australia was made in 1969 by a Senate Select Committee. A considerable amount of information relevant to problems, legislative controls and other facets of pollution from mining activities was put before this Committee in evidence. The report of the Committee is expected to be presented to the Federal Parliament during 1970. Little purpose could be gained by attempting to recover the same ground in this project and the reader is referred to the Senate Report for further information on Australian problems.

However, it seems pertinent to draw attention to the major sources of information available in overseas studies. Coal mine drainage is a major pollution problem in the U.S.A. and a number of reports describe the magnitude of the problem. McCarren (ref. 55) reported that 1000 miles of streams in the Allegheny River are affected. Lorenz and Stephan (ref. 56) report that coal mine drainage pollutes more than 5000 miles of streams in the Appalachian region. Cleary (ref. 57) reviews the problem in the Ohio River Valley. The Ohio River Valley Water Sanitation Commission has prepared a handbook for control of acid mine drainage waters.

Abstracts of publications on mine drainage are prepared in the U.S.A. A supplement to the 1966 Mine Drainage Abstracts (ref. 58) gives abstracts of 255 relevant papers published in the period 1910-1966. The June, 1968 issue of the Journal of the Water Pollution Control Federation includes a review of literature in 1967 on wastewater and water pollution control. The section on "Coal and Coal Mine Drainage", p.1158, reviews 39 papers and reports.

In other countries, Gupta and Mukherjee (ref. 59) review the problem in India; Kemp (ref. 60) reports on the problem in South Africa; and Ajuria (ref. 61) describes pollution from coal mine wastes in Spain.

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CHAPTER 6

IRRIGATION

6.1 INTRODUCTION

Irrigation is a very large consumer of water. The amount used in applying 1 foot depth of water to one acre of ground would be sufficient to provide 15 people with 50 gallons per head per day for one year. Large scale irrigation development substantially alters the hydrologic regime of a river basin by increasing the evapotranspiration loss and reducing the amount of water available for other purposes.

However, the more permanent effect of irrigation development, and the more difficult problem to manage, is that of salinity. Almost all natural waters contain some soluble salts. These derive from the weathering and breakdown of rock materials, or they may derive from the leaching of sedimentary rocks which were formed under a saline sea, or salts of oceanic origin may be deposited on a catchment by rain.

In irrigated areas, where subsurface drains collect any excess from overwatering, the amount of salt passing through the system is not altered but the amount of water is substantially reduced by evapotranspiration loss. Consequently, the salinity of the drainage waters is usually substantially higher than the salinity of the irrigation supply. In areas where there is inadequate drainage, either natural or artificial, overwatering usually results in a rapid rise in groundwater levels and water-logging when the watertable reaches the surface. If the groundwater is saline, as often occurs in Australia, salt accumulates at the surface as water evaporates, and salinization of the land results.

On a small irrigated area, salinity is not a difficult problem to handle. A predetermined amount of overwatering, based on the amounts of salt in the soil and the supply water, can result in continuous leaching of salt beyond the root zone of the irrigated crop and prevent any accumulation. If natural drainage is inadequate to stop the excess water from raising the watertable, drainage can usually remedy or avoid the problem. Drainage effluents from small irrigated areas are usually not major sources of pollution.

However, when very large areas are irrigated, the total amount of drainage effluent and the total quantity of salt for disposal can be very large. If this waste must be returned into the river channel and carried downstream in the river to the sea, the quality of water downstream of the irrigated area can be seriously degraded.

In Australia, the major areas of large scale irrigation development have been around the Murray River and its tributaries. Problems of waterlogging, salinization, and degradation of water quality in the lower reaches of the river, have occurred. Management of salt is now a major problem in the operation of the river. In the following section, a description is given of irrigation development in the Murray Basin and the problems of salinity which have arisen. For comparison, descriptions are given in succeeding sections of other areas of large scale irrigation development which have encountered similar problems. In the final section an outline is given of the current state-of-the-art of salinity management, including knowledge of their movement and behaviour, and the criteria which are used to estimate the salt-tolerance of crops and animals.

6.2 SALINITY PROBLEMS IN IRRIGATED AREAS

6.2.1 The Murray River System

The Murray River and its tributaries form the largest single river basin in Australia covering 408,000 square miles, about one-seventh of the total area of the continent. The biggest tributary, the Darling River, is regulated by weirs and the Menindee Lakes storages, and contributes to the regulation of flow in the lower Murray; however, this tributary is not part of the large-scale irrigation development or the problems of salinity.

The Murray was used extensively for navigation in the early days of expansion of white settlement, with paddle steamers trading 1000 miles up river to Euchuca and some as far as Albury. Of the 14 locks built on the river between Hume reservoir and the mouth, 13 are fitted with navigation locks. At present, these serve mainly small craft used for pleasure and sport.

The first irrigation scheme in the Murray Basin was commenced in Victoria in the 1870's in the Kerang area. In 1887, irrigation schemes were initiated by the Chaffey Brothers at Mildura and Renmark. By the turn of the century, it was officially accepted that the use of water for irrigation was the major concern as opposed to the maintenance of a navigable depth of water in the river.

In recent times, the supply of water to towns along and close to the river has become increasingly important, particularly in South Australia which, lacking other major rivers, is most dependant upon the Murray.

From the 1880's, conflicting demands occurred between navigation and irrigation, and there were disagreements among the states of New South Wales, Victoria, and South Australia as to the use of available water. Following a Royal Commission in 1902 and interstate conferences, agreement was reached in 1914 which resulted in the River Murray Waters Act, ratified in the parliaments of the Commonwealth and of the three states in 1915, and the establishment of the River Murray Commission.

The Murray Basin can be conveniently considered in 3 zones - Upland, Riverine Plain, and Mallee. There are two primary salinity problems associated with irrigation development. These are (1) shallow and highly saline watertables in the Riverine Plains; and (2) high salinity in the river water in the Mallee region.

The main supply of runoff water comes from the well-watered Upland. Quality is very good for irrigation with average soluble salt contents in the order of 40 p.p.m. The average salinity of rainfall on the catchment is of the order of 5 p.p.m. and it seems clear that the dominant source of salt arising in the Uplands is from rock weathering and the leaching of salt from sedimentary rocks. However, the quality of this supply water is very good for irrigation and the much higher salinities which occur in the river water further downstream derive from the Riverine Plain.

The Riverine Plain is characterised by shallow groundwaters, most of which are highly saline. Natural drainage is poor, and channel seepage and overwatering from irrigation has raised the watertables with subsequent water-logging, and salinization where the groundwater is saline. With the rise in watertables, the discharge of saline ground-water into the base flow of the rivers has also risen, particularly after rain.

The four major Murray areas of irrigation development in the Riverine Plain are the Kerang and Shepparton regions in Victoria, and Deniliquin and Wakool regions in New South Wales. The Shepparton region suffers from waterlogging but no significant salinity problems. In the Kerang region, there are widespread shallow groundwaters which are saline. This region suffers markedly from salinization of the soil, and contributes a considerable salt load to the Murray River. The Deniliquin region in New South Wales has no problems with shallow watertables at present, but it seems probale that these will develop in time. The Wakool region has suffered water-table problems for some time and the groundwater is saline.

In addition to these Murray regions, there is the Murrumbidgee Region which includes the Irrigation Areas of Murrumbidgee, Hay, and Coleambally. This region is of less importance in the subject of this chapter because it contributes little salinity to the Murray; in fact, flow from the Murrumbidgee is important from the viewpoint of river management because of the significant dilution effect it has on Murray water downstream of the junction of the two rivers.

Because of the salt loads from other tributaries entering the Murray in the Riverine Plain, the salinity of the river water increases steadily from Hume Reservoir downstream to the mouth. The Mallee Zone commences near Swan Hill and includes the Sunraysia region, stretching to the South Australian border, and the South Australian region. In South Australia, the river flows in an incised channel and salt accessions to the river are from the generally saline groundwaters. This salt added to that brought down from the Riverine Plain produces salinities which reach critical levels in periods of low flow. The majority of irrigated land above Mannum in South Australia is devoted to horticultural crops, including stone fruits and citrus which are particularly salt-sensitive. It is the salinity of the river supply water that is important in this region.

Salinity control in the Murray River is a complex problem involving the disposal of some very high saline waters into evaporation basins, and the regulation of flow by many dams to control quality by dilution. Pels (ref. 2) in 1967 put forward a proposal that high quality water be diverted from above the entry of the Goulburn tributary into a channel to supply Sunraysia and South Australia leaving the lower reaches of the Murray as a drain to carry away low quality wastewaters.

A major report on salinity in the Murray River has been commissioned by the River Murray Commission and is now approaching completion. This report will contain an extensive review of the salinity problem, discussion of various proposals for control, and a bibliography of relevant papers and reports. The reader who is interested in detailed aspects of the problem is referred to this report (ref. 1).

6.2.2 Indus Valley, West Pakistan

The Indus Valley in West Pakistan has supported irrigated agriculture for over 4000 years. The rivers rise in the Himalayas and flow southwest through very dry country bordering on the Indian desert. It has been estimated that the average annual flow in the valley is 170 million acre feet. The plain is very flat with gradients about 1 foot per mile from the upper edge of the irrigated area to the coast.

The present irrigation system was originated by British engineers in the middle of the 19th century. Several large barrages were constructed across the Indus and its tributaries, and about 75,000 miles of canals were dug. Large tracts of desert were developed to fertile farming areas.

The problems of inadequate drainage and overwatering were not escaped. The alluvium extends for many hundreds of feet and is highly pervious. The groundwater was originally at great depth, but after the turn of the century, it began to rise at about $1\frac{1}{2}$ feet per year. Leakage from unlined canals added to the problem of overwatering in the irrigated areas. When the watertable came to within a few feet of the surface, salt accumulated as the water evaporated, and the problems of salinity and waterlogging resulted in considerable areas of land being lost to cultivation. It was estimated that, in the early 1960's, about 100,000 acres of land were being lost each year. The magnitude of the problem equalled the magnitude of development in the valley, one of the great areas of irrigated agriculture in all history.

The physical problem in the Indus is matched by the political problem of the area. When India and Pakistan were partitioned in 1947, the irrigated lands became part of Pakistan because of the predominantly Muslim population. However, the headwaters of the rivers arise in India and there have been problems over sharing of the available waters. Birkhead (ref. 3) describes the political problems and institutional arrangements which now govern the operation of the area.

In addition to the large amounts of overseas money contributed for development and improvement of the Valley, a large amount of expert technical assistance was provided. The major investigation, undertaken by the Water Resources group at Harvard University, (see ref. 4) put forward a solution for use of about 32,000 tube wells spaced at about 1 mile centres. With this system, the watertable was lowered by pumping and the pumped water, mixed with fresh supplies, was used to leach salt from the root zone by the water circulation which resulted. Agricultural production could then be further raised by proper use of fertilizers, pesticides, farm equipment and better management. Fiering (ref. 6) gives a description of the computer simulation analysis used to optimise the components of the system.

6.2.3 Irrigation Systems in California

The principles of salt balance, and methods of analysing the supply, movement, and final disposition of salt in an entire river system can be further illustrated by examples of some irrigated areas in California. These examples well illustrate the state-of-the-art of analysis, and the development of computer simulation models for water quality, similar to the water balance simulation in mathematical catchment models.

The Coachella Valley provides a good example of salt balance in an irrigated area. Irrigation has been developed on about 60,000 acres in the valley, using water diverted from the Colorado River by the Boulder Dam. The climate of the valley is hot and arid with mean temperature about 73°F and annual rainfall averaging 3 inches.

In anticipation of restricted drainage of excess waters from beneath the irrigated areas, a series of observation wells was installed as early as 1948. As expected, the irrigation activity caused the development of a shallow semi-perched body of groundwater beneath the irrigated land and extensive tile drainage was installed. The nature of the sediments extending to a depth of 100 feet beneath the irrigated land is such that there is no significant downward movement of drainage water to the underlying aquifer.

The supply canal is concrete lined and water to each block of 40 acres is distributed through underground concrete pipes, and is metered. The operations in the valley provide a good opportunity to study salt and water balance in an irrigated area because both salt and water inflow and outlfow are monitored.

Bower, Spencer and Weeks (ref. 7) analysed data on salt and water balance for the period 1957-1965 and found that the salt balance index (ratio of output of salt to input of salt) was highly related to both the area of irrigated land having tile drainage and the leaching percentage. The index approached one when about half the irrigated land became tiled and when the leaching percentage increased to about 30.

At salt balance, evapotranspiration was calculated as the difference between applied water and drainage water, and this was found to agree within about 10% of that calculated by the Blaney-Criddle formula. Comparisons of the compositions of irrigation and drainage waters at salt balance indicated that about 10% of the applied salt precipitates in the soil largely as calcium carbonate, and that calcium and magnesium in water replace exchangeable sodium in the soil during irrigation operations.

The San Joaquin Valley in California contains about 4 million acres of irrigated land, about one-half of the total valley floor area. In addition to the natural water resources of the valley, development works such as the Central Valley Project import a combined total of about $4\frac{1}{2}$ million acre feet per year. It has been estimated that in 1960, irrigation usage of water in the area was about 9 million acre feet out of a total available of 13 million acre feet.

The impending problems of salt accumulations and high water tables have been recognised. Berry and Stetson (ref. 9) have described the drainage problems of the area and early efforts towards a solution. Huffman (ref. 10) describes the results of an investigation of how the drainage waters from farms and from pumping for groundwater control are in part mixed with incoming water of high quality for re-use, the balance becoming waste water for disposal. Huffman's figures show that the amount of waste water is expected to increase continuously to an amount of about 500,000 acre feet per annum by the year 2000.

The Californian Department of Water Resources has studied various ways of disposing of the waste water - by desalting, by evaporation basins, and by transportation to the sea in a canal. Desalting was found to be much higher in cost than the other methods. Evaporation was studied in detail, including studies of how much sprinklers and salt tolerant trees might increase the rate of evapotranspiration. There were local advantages of evaporation ponds in the southern part of the valley but, overall, the cost was about 50% higher than disposal by transportation.

The best solution was a master drain down the trough of the valley, lined to prevent percolation of highly saline water into underlying aquifers, and incorporating a regulating reservoir to receive peak flows in summer and autumn and provide a uniform discharge through the year. The ultimate disposal point of waste waters will be near the natural discharge of the river near the San Francisco bay area. Dilution facilities will be provided to raise the quality of the discharge as required.

A problem in this valley is the nutrient content in the waste waters from leaching of fertilizers in the agricultural areas. The Department of Water Resources has studied the use of algae to utilise nitrogen and phosphate in the water with subsequent harvesting and disposal of the algae. Chlorinated hydrocarbon pesticides are not expected to become a serious problem.

The Sacramento River in California has been highly developed for irrigation with 21 separate irrigation districts in the Valley. The river is regulated by the Shasta and Keswick dams of the Bureau of Reclamation's Central Valley Project. The system is drained by the river itself and by a system of agricultural drains. Orlob and Woods (ref. 8) report that during the peak of the 1960 irrigation season, releases from Keswick dam were about 21,000 acre feet per day to meet irrigation requirements.

The principal interest of this system for the present project is the hydrologic simulation model which has been developed of the entire river system. The model, which is described by Orlob and Woods, is a mathematical model using a digital computer to simulate both the water balance of the river system and changes in water quality along the river due to irrigation use.

The water balance model balances changes in soil moisture, groundwater and river storage in a number of individual components of the system which represent irrigated areas, reservoirs, reaches of the river, etc. The interactions between the components are also simulated to represent the dynamic behaviour of the whole system. Data used to check the simulation are gauged main river flows, drainage returns, flows in principal tributaries, accretions to groundwater, calculated evapotranspiration loss, and measured rainfalls.

The simulation of change in water quality is based on concentration of salts as water is removed by evapotranspiration in the irrigated areas. The authors assume the pollutants are conservative i.e. do not decay or react with soil, etc., in the system, and the calculated "use factor" as water moves down the river system was found to be reasonably well correlated with measured electrical conductivity, total hardness, sodium concentration, and bicarbonate alkalinity. Recognising the limitations of the model, the authors set out requirements for an improved model which incorporates decay and interaction. They suggest the three (3) main requirements of a water quality model are:-

(i) compatibility with a dynamic hydrologic model of the same system;

(ii) facility for accommodating time-dependent decay functions;

(iii) facility for time-delay of quality constituents brought about by interaction with the physical media through which the constituent must pass.

6.3 SALINITY PRINCIPLES

6.3.1 General Review of Literature

The information which has been published on irrigation and salinity is vast. The International Sourcebook on Irrigation and Drainage of Arid Lands in Relation to Salinity and Alkalinity, published as a draft in 1967 by UNESCO (ref. 11), gives a broad survey of the subject by many specialists, and includes reference lists with every chapter. This book is probably the most authoritative statement of knowledge and practice related to salinity yet prepared.

A world-wide exchange of information on irrigation research and practice is organised by the International Commission on Irrigation and Drainage, whose permanent headquarters is in New Delhi. The ICID was set up in 1950 under the sponsorship of the government of India, and some 60 countries at present participate in its activities. International congresses have been held in India (1951), Algeria (1954), U.S.A. (1957), Spain (1960), Japan (1963), India (1966), and Mexico (1969). The transactions of these congresses contain information on both theoretical and practical aspects of irrigation. An annual bulletin is published on research and technical advances in irrigation, drainage, river control, and flood control, together with an annual bibliography.

Many other bibliographies have been prepared from time to time. There are two annotated bibliographies on reclamation and improvement of saline and sodic soils, prepared at the Institute for Land Reclamation and Improvement at Wageningen in the Netherlands (refs. 12, 13). In Australia, there is a bibliography of C.S.I.R.O. publications or on irrigation, drainage, and related subjects, compiled at the Commonwealth Research Station, Merbein, Victoria (ref. 14), and Margaret Russell (ref. 15) has compiled a bibliography of publications by officers of the Commonwealth Research Station at Merbein and the Irrigation Research Station at Griffith, N.S.W., from 1923 to 1956.

Slatyer and Mabbutt (ref. 17) describe some aspects of the salinity problem in irrigated agriculture in their section, "Hydrology of Arid and Semi-arid Regions", contained in the "Handbook of Applied Hydrology", edited by Ven Te Chow. At the National Symposium on the Use and Management of Water Resources, held in Canberra from 9 to 13 September 1963, England (ref. 18) and Forster (ref. 19) reviewed the problem, and there have been some symposia in Australia devoted to salinity (e.g. ref. 20). Marshall (ref. 21) and more recently Talsma (ref. 22) give excellent reviews of the soil physics background to salinization.

The Victorian Irrigation Research and Advisory Services Committee (VIRASC) has compiled an excellent review (ref. 28) of information on the suitability of water for various agricultural and related uses. A list of relevant references is included at the end of each chapter of this publication.

6.3.2 Sources of Salt

The original sources of salts in water are the primary minerals derived by the breakdown of rocks and soil particles in the earth's crust. Soluble constituents are gradually released as a result of chemical decomposition and physical weathering. In humid areas, there is a steady leaching of soluble materials from the soil and rocks, into groundwater, thence into rivers and to the sea.

Salt particles can also be taken up into the atmosphere from the surface of the sea and deposited on a catchment in rain. Salt is taken up from spray at the tops of waves and the bursting of bubbles at the surface of the sea. Large amounts of salt, in the order of 125 lbs/acre/year, can be deposited in rain near the coast but the amount decreases to less than 5 lbs/acre/year in inland areas of Australia. This type of salt is usually termed "cyclic salt" to indicate the cycle from sea to land via the air, and return to the sea in drainage waters.

Chebotarev (ref. 23) gives a useful account of the origin of saline water. Gorham (ref. 24) and Hem (ref. 25) give good reviews of the factors affecting the supply of major ions into water. Cope (ref. 26) gives a very good account of the sources of salt in catchments in Victoria and this includes a good review of the literature which deals with cyclic salt. Powell (ref. 27) gives a general description of the constituents which affect the quality of water and of sampling and analytical procedures.

6.3.3 Quality Criteria

Because the irrigated lands of many ancient civilizations have become saline and unproductive, man has probably known of the effects of salts on plant growth throughout recorded history. However, detailed criteria of the salt tolerance of crops, and of animals, dates only from this century.

Soluble salts in soil water raise the osmotic pressure and reduce the ability of plants to take up the water. Robinson (ref. 29) gives a detailed description of the effects of salt on plants and how plant damage can occur.

Different plant species vary widely in their tolerance to salts, and the tolerance of many crops has been determined. The United States Salinity Laboratory has published (ref. 30) a considerable amount of information on the salt tolerance of irrigated crops. Information suitable for use in Australia has been summarised in the draft Standard's Association Code of Practice for Sprinkler Irrigation Design (ref. 31), and in the publication by the Victorian Irrigation Research and Advisory Services Committee (ref. 28).

The major ions in irrigation water are the cations calcium, magnesium, and sodium; and the anions bicarbonate, sulphate, and chloride. Other ions that may be found are potassium, carbonate, nitrate, silica, iron, and boron, but these are usually in low concentrations.

Four major characteristics determine the quality of water for irrigation. These are:-

(i) total concentration of soluble salts

(ii) the proportion of sodium to calcium plus magnesium

(iii) the concentration of bicarbonate

(iv) the occurrence of highly toxic minor elements such as boron.

If the proportion of sodium is high, it may be adsorbed on the soil particles and result in an unfavourable physical condition. Such soils, when wet, tend to run together and impede the movement of water and air. When dry, they form hard clods. Irrigation waters with high sodium percentages require special management practices.

Waters that are low in total salts but high in bicarbonate can also be dangerous if the bicarbonate is considerably in excess of the calcium and magnesium present. The excess bicarbonate over calcium plus magnesium is referred to as residual sodium carbonate. When an irrigation water containing residual sodium carbonate evaporates in the soil, calcium and magnesium carbonates precipitate and the sodium percentage of the soil solution increases. The sodium replaces calcium on the soil particles, the exchangeable-sodium percentage of the soil increases and the physical condition of the soil deteriorates.

The United States Salinity Laboratory has developed the "sodium - adsorption - ratio" (S.A.R.) as having the best-fit empirical relationship to the exchangeable-sodium-percentage of the soil (see ref. 30).

$$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{++} + Mg^{++}}{2}}}$$

The S.A.R. is an index of how and to what extent a given water containing excess sodium might change the permeability and structural properties of a soil. The higher the S.A.R., the greater the adverse effects. Quirk (ref. 32) gives a review of those aspects of salinity which are related to the chemical and physical behaviour of soils.

Boron is a minor constituent of practically all natural waters and is essential for the growth of plants; however, it may be toxic in concentrations only slightly in excess of those needed for optimum growth. Sensitive plants may be affected at concentrations below 0.5 ppm and almost all plants are affected above 4 ppm. Although the boron tolerance of most plants is well established, there is little remedial action which can be taken if an excess is present, other than to obtain an alternative irrigation supply.

Jewitt (ref. 33) gives a good summary of the salts contained in the waters of the Murray and its tributaries. In the same symposium, Potter (ref. 34) discusses the tolerance of sheep and cattle to salinity of their drinking water. The Victorian Irrigation Research and Advisory Services Committee has collated available Australian information on the salt tolerance of stock, and they provide reference to published Australian data (ref. 28).

6.3.4 Principles of Salt Balance

Any salts brought into the root zone of an irrigated crop in the supply water will remain while the water is removed by evapotranspiration, and will accumulate unless leached out. To achieve a salt balance, additional water in excess of the evapotranspiration requirement must be applied to wash the salts remaining from the previous irrigation application to below the root zone. Where natural drainage is inadequate to allow ready discharge of the leaching water away from the area, artificial drainage will be required to prevent the water table from being raised too close to the surface. When saline groundwaters are raised to within a few feet of the surface, water will evaporate and salinization of the soil occurs as salt accumulates in the upper soil layers.

In 1937, Hill (ref. 36) developed the concept of "equivalent service" which is that, because evapotranspiration is continuously removing water, the salt concentration of the remaining soil moisture is increasing except when moisture is percolating downwards from rainfall or irrigation. Thus, application of an increased quantity of a more saline irrigation water can lead to the same mean salt concentration in the soil moisture of the plant root zone as will result from less frequent applications of a less saline water. Applying an excess of irrigation water causes a part of the applied water to pass below the root zone and become drainage water.

In Australia, the simpler and correct concept of "leaching requirement" (ref. 30) has become more accepted. From measurement of the electrical conductivity of the applied water and knowledge of the salt tolerance of the crop, the amount of additional water needed for leaching in excess of the evapotranspiration requirement, can be calculated. The method of calculation is set out in the Draft Code of Practice for Sprinkler Irrigation Design (ref. 31) and in ref. 28.

Some of the applied water will move rapidly through the larger pores and reach the lower boundary of the root zone with little increase in salt content. On the other hand, water moving through the finer pores may displace soil water essentially as piston flow, so that drainage from the smaller pores will have about the same salt concentration as that of the soil water in the root zone. The water draining from the root zone is therefore a mixture of unchanged irrigation water and displaced soil water, and the fraction that is formed of soil water has been called the "leaching efficiency" by Boumans and van der Molen (refer to Bouwer, ref. 37). Actual values of the efficiency have been calculated from salt balance data for 3 irrigated regions by Bouwer (ref. 37), the regions being the San Joaquin Valley and the Coachella Valley in California, and the Murray River in Australia.

Scofield (ref. 38) developed the concept of salt balance applied to a whole catchment in contract with the salt balance at a point in an irrigated area. The principle is that, although man may use part of water supply in a river for the irrigation of crops, all of the salt in that water must eventually be passed downstream. Another requirement of salt balance is that all the excess salts initially in the root zone of saline soils must be leached out to reclaim such soils.

Pillsbury and Blaney (ref. 39) review the problems and principles of salt balance in river systems and conclude that "degradation of water with progress downstream is inevitable if the use of the water resource is to be maximised."

These authors introduced the term "degradation ratio" which is the fractional equivalent of degraded water to good water, e.g. 1,000 acre feet of water with an EC of mmhos per cm would be equivalent in irrigation potential to 600 acre feet of high quality water. Because of the need for more frequent irrigations, increased drainage facilities, and other requirements, the actual cost of using degraded water could be much higher than the degradation ratio suggests.

6.4 SUMMARY OF INFORMATION ON IRRIGATION

The major problems of salinity resulting from irrigation development in Australia are associated with the Murray River and its tributaries. A major report has just been prepared for the River Murray Commission which gives a comprehensive review of the problem and an excellent bibliography of relevant Australian publications.

Salinity and waterlogging problems have occurred frequently in areas of large scale irrigation development throughout the world. The major sources of salt are known, the principles of salt movement and behaviour are understood, and there is a well-established technology for managing salt in river systems. Following the development of high speed digital computers there have been developments in mathematical models for predicting the movement and behaviour of salts in river systems and irrigated areas, mainly in the U.S.A.

Understanding of salinity principles by research workers in Australia seems to be of a high standard when compared with other countries. The use of digital simulation methods for analysing large-scale salt movement in river systems has only recently been explored in this country; but these methods are very new and still in a state of development in the U.S.A.

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CHAPTER 7

REVIEW AND CLASSIFICATION OF METHODS

7.1 INTRODUCTION

There is a profusion of methods and techniques used to study the hydrologic effects of change in land use, and the choice of method is frequently as important as the results obtained. Where the method used is of doubtful validity, the results cannot be accepted without question.

The studies reported in other sections of this report have used a variety of techniques and types of study area. Data has been collected from fractional-acre plots, unit source areas, small experimental catchments, large representative basins, and such others as barometer watersheds, vigil networks, and benchmark basins. Data analysis ranges from simple graphical techniques relying on visual examination of plotted data, to the most sophisticated of statistical procedures.

There has been little systematic study or development of the methods used. Standard hydrologic texts do not deal with experimental catchments or methods of experimental design, and there are no established manuals of practice which set out details of how to identify a unit source area, how to set up a paired or multiple catchment experiment, or even what criteria should be used to identify and evaluate changes in runoff.

One objective of this project has been to review past methodology, to identify weaknesses in the approaches used, and to suggest the methods which offer best prospects for future studies. In this chapter, a review is made of methods which have already been used in order to put past studies in perspective, and a classification system is outlined.

7.2 THE METHODS

The literature dealing with studies of hydrological effects from changes in land use lacks a systematic classification of the different methods used. Some ordering of the methods is desirable in order to see each method in perspective and to make comparisons. Existing classifications do not seem adequate. For example, the American Geophysical Union (ref. 2) classes watersheds used in research studies into two principal categories:- experimental watersheds and representative watersheds. They state -

"an experimental watershed is one that has been chosen and instrumented for study of hydrologic phenomena; a representative watershed is one that has been chosen and instrumented to represent a broad area in lieu of making measurements on all watersheds."

The Director of the Office of Water Resources Research of the U.S. Departments of the Interior (Renne, ref. 41) quotes this classification and comments that -

"studies using experimental watersheds imply a search for principles, relationships, and factors for prediction schemes; studies using representative watersheds imply that data are transferred quite directly to other watersheds where similar measurements are not available."

This classification has some weaknesses. Apart from being very broad, it is not well defined. Some groups of representative basins are specifically intended for study of basic relationships, for example, the Australian system of representative basins is being selected "for detailed study, particularly of rainfall-runoff relationships." (Australian Water Resources Council, ref. 7, p.4).

The following classification system, which encompasses both methods of data collection and methods of data analysis, has been proposed by Boughton (ref. 13) as an alternative.

- Collection of data
  - Observational Methods
    - Plots
    - Unit Source Areas
    - Barometer Watersheds
    - Representative Basins
    - Vigil Basins
    - Benchmark Basins
  - Experimental Methods
    - Calibrated Catchments
    - Paired Catchments
    - Multiple-catchment experiments
- Analysis of data
  - Statistical
    - Graphical Analysis
    - Single-variable analysis
    - Multi-variable analysis
  - Physical
    - Mathematical Models
    - Physical Models
    - Analogue models

The separation of data collection from data analysis serves principally for the review of past studies which is made here, but is not the most suitable approach to planning of land use experiments. Integrated studies where collection of data is planned in conjunction with analysis of data are the ideal.

7.3 COLLECTION OF DATA - OBSERVATIONAL METHODS

A variety of methods of data collection have been used in experiments and projects to evaluate land use effects. The methods range from the purely passive, or observational, to the active, or experimental, approach. This distinction between observational and experimental is adopted as a primary separation in the classification of methods of data collection.

With observational methods, the observer plays a passive role by observing the behaviour of different catchments, and attempting to deduce by analysis the influence of catchment characteristics or land use on the observed variable, usually runoff or sediment yield. With experimental methods, the experimenter introduces a deliberate change to some part of the catchment system, and then attempts to monitor the effects produced by that change.

Observational methods encompass both large complex situations as in representative basins and smaller, more homogeneous situations as in runoff and soil loss plots. Unit source areas are between these extremes in both size and homogeneity. Experimental methods include "before and after" studies of a single catchment, comparisons of different catchments in paired-catchment studies, and multiple-watershed experiments in which many catchments and many treatments are involved. These methods are described in the following sections.

(i) Plots

The two basic ideas behind the use of small plots for hydrologic studies are firstly that, being small, it should be possible to select different sites with variation in only one factor (such as slope, soil type, land use, etc.), and, secondly, being cheap, sufficient replications could be made to ensure statistical significance of the results. Rarely, if ever, are these ideals attained or even adequately pursued in practice.

Hayward (refs. 27, 28) has made a comprehensive review of plot experiments, particularly those directed towards soil loss. This study has shown the wide range of plots which have been used, ranging from a few square feet to several thousand square feet in area.

This review has also shown up two major weaknesses which typify most plot studies - lack of statistical design and analysis of the experiments, and, more specifically, disregard for any bias created by the boundaries of the plot. Fractional-acre plots in particular are so small that boundary effects can completely dominate natural effects. Interference with the natural overland flow pattern and wind blow of rain and soil particles into the collecting gutters can create quite considerable errors in the data collected from plots. The need to allow for such effects in plot experiments has been set out elsewhere, (Boughton, ref. 14).

There are few results from plot studies related to land-use evaluation which are valid, quantitative, and statistically significant. In addition, the study by Minshall and Jamison (ref. 36) shows clearly the differences which can occur between watershed runoff and runoff from plots within the watershed due to both interflow and transmission losses. The problems of bias inherent in the collection of data from plots are thus compounded by the problems of extrapolation from the plot to the whole watershed.

Before plots could be used with confidence for land-use evaluation studies, some basic investigations of the following would be needed:-

(a) to establish the degree of bias to data caused by the nature of the plot construction.

(b) to establish the variance within so-called homogeneous areas which plots are used to sample.

(c) to clarify the differences between plot runoff and watershed runoff due to interflow and transmission losses.

(ii) <u>Unit Source Areas</u>

The unit source area is an approach to isolation of the factors affecting runoff and soil loss which is intermediate between plots and large catchments.

A unit source area is presumed to have relatively homogeneous soils and vegetation cover, uniform precipitation, and geologic influences on the surface outflow which are areally representative (Kincaid et al, ref. 33). Amerman (ref. 3) defines a unit source area as "a sub-division of a complex watershed which, ideally, has a single cover, a single soil type, and is otherwise physically homogeneous."

The underlying concept is that complex watershed runoff is essentially a summation of the runoff contributions from its component unit source areas. Unit source areas that are sufficiently alike are assumed to react in a similar manner hydrologically when they are subject to storms that are alike. Amerman says:-

"by prediction and combination of unit source area runoff, it should be possible to predict runoff from ungauged complex watersheds. In this manner, the integrated effects on runoff of various combinations of land use changes on a complex watershed may be calculated without actually measuring and evaluating runoff from other complex watersheds to which the several plans have been applied."

The runoff computed from unit source areas at Coshocton did not agree with observed runoff in the examples quoted by Amerman, but linear regression equations between computed and observed data gave correlation coefficients of 0.98 for a 76 acre watershed and 0.99 for a 7.4 acre watershed. Amerman suggests that the disagreement in direct comparison may be due to:-

(1) interflow
(2) partial area runoff
(3) influence of runoff from upslope areas upon runoff production on downslope unit source areas.

Amerman and McGuinness (ref. 4) discuss this problem of extending from small areas to large complex watersheds. These authors give the following definition of unit source watersheds:-

"Unit source watersheds are defined as all research watersheds, plots included, whose data are to be applied directly to larger watersheds."

Robins, Kelly and Hamon (ref. 42) propose the use of unit source watersheds as a basis for hydrologic study of a 93-sq. mile experimental catchment in Idaho, but this report and the others cited omit any detailed specification for delineating unit source types and for classifying sub-areas of catchments into these types. Amerman also cites unit source studies by Rowe (ref. 44) and Allis (ref. 5). Doty and Carter (ref. 24) use unit source areas for study of the rates and particle size distributions in soil erosion.

A Unit Source Watershed Conference was held at St. Louis, Missouri, U.S.A., in February 1965, indicating the American interest in this method of research; however, unit source methods are virtually unused in Australia. While the concept is attractive because of its relative simplicity, the following apparent weaknesses require some resolution before the method would be satisfactory for land use studies:-

(a) the present lack of specifications for classifying and identifying unit source areas.

(b) the lack of data on differences in the response of unit source areas of the same type, i.e. the within-type variation which will determine the significance of between-type variation.

(c) the unknown effects of interflow, partial area runoff, and transmission loss in extrapolation from unit source areas to whole catchments.

(iii) Barometer Watersheds

Dortignac and Beattie (ref. 23) describe a catchment unit that seems to be a special type of representative basin. These watersheds, used by the U.S. Forest Service, are termed "barometer watersheds" and are stated to be "50,000 to 150,000 acres in area (80 sq. miles to 240 sq. miles) selected to represent a broad climatic-physiographic region."

These catchments are surveyed in detail with measurements of water storage capacities of soil and rock, vegetative composition, ground cover etc. Sampling techniques are applied to the measurements to ensure accuracy. The data obtained are combined in a water balance analysis which accounts completely for the disposition of precipitation from the moment snow or rain strikes water surface, soil, rock or vegetation, through all of the runoff or percolation processes until the precipitation is accounted for as runoff past the gauging station or as deep percolation.

Parameters in this analysis are adjusted (not stated how) until hydrographs are reproduced "with reasonable accuracy" whence the watershed is "adequately characterised or calibrated". Extrapolation to other areas is not clearly explained.

The approach described in the paper by Dortignac and Beattie could be sound. The problem in reviewing the concept of "barometer watersheds" is that insufficient information is available on two important fundamental aspects:-

(a) how parameters in the water balance model are adjusted in order to calibrate the catchment.

(b) what criteria and methods are used to extrapolate the results from one watershed to other areas.

(iv) Representative Basins

The concept of a representative basin arises from the fact that the land surface of the earth contains a number of recognisably different landscapes, i.e. types of country as determined by geology, topography, land-use, etc., and that within each landscape a catchment or catchments may be selected which are representative of the catchments which form the landscape. Hydrological similarity among the catchments of the region is presumed.

Generally, the boundaries of such regions are determined by climatic zones, lithology, and landform. The region need not be in a virgin condition and, usually, virgin-condition catchments of a representative nature are treated separately as Benchmark or Vigil Basins (see later sections). However, a representative basin should be developed to the same extent as, and have the same land-use, as the region in general.

Representative basins form the other extreme in size and complexity to plots in the range of observational methods used in land-use studies in hydrology. The concept of a representative basin may have preceded the International Hydrological Decade (I.H.D.) but it was the I.H.D. programme in which this terminology was formalised. Descriptions contained in I.H.D. reports give a wide range of sizes of representative basins, recently given as generally from 1 to 250 sq. km. and rarely in excess of 1000 sq. km.

In countries where a network of representative basins is to be gauged, data will be recorded from a wide range of catchments, and it is probable that data will be obtained from some landscapes that otherwise may not have been included in the national network. However, the scientific merit of representative basins is not at all clear and the value of the data collected, beyond routine assessment of national water resources, is open to question.

The underlying concept that repeating units in a landscape are hydrologically identical, or at least sufficiently similar for one catchment to be representative of the group, has never been established. The few studies which have examined catchments on a regional basis and examined the differences between regions, for example Sopper and Lull (ref. 50) or Ivanov and Romanov (ref. 32), give the impression that there is as much hydrological variation among the catchments in a region as there is between those of different regions.

It would be wrong to condemn the collection of data from catchments in such diverse landscapes as will be included in representative basin networks. Indeed, there is still a great need for collection of data on many such catchments in Australia. However, there could be danger in use of the term "representative" if it is allowed to convey the impression that hydrological similarity of catchments in a region is a proven fact, and that data from one such catchment may be extrapolated directly to other catchments in the same region.

The report of the 1st Session of the Co-ordinating Council of the I.H.D., held in Paris in May 1965, mentions Decade Stations, Benchmark Basins, and Vigil Basins in addition to Representative Basins.

Decade Stations describe the minimum essential stream gauging network, i.e. the stations of major significance for defining the water resources of a country, or stations which are established to assess the resources of an area which is under special examination for development purposes. It seems that this class of station is of more concern to countries with stream gauging networks less developed than in Australia. Benchmark and Vigil Basins are more related to the topic of this report and are described separately in the following sections.

(v) <u>Benchmark Basins</u>

The following is quoted from the Report of the 1st Session of the Co-ordinating Council of the I.H.D. :-

"By exploitation of resources, man's mark upon his own environment becomes ever deeper and more drastic. On the other hand, changes in climatic patterns, through their effects on the hydrological cycle, on soil, and on vegetation can produce results remarkably similar to those caused by the works of man. Among natural phenomena, the most pervasive and probably the most important are the slow and subtle changes in land, vegetation and water which result directly or indirectly from variations in climate. Over periods of time, pulsations in precipitation and temperature regimes cause changes in evapotranspiration, in soil-moisture recharge, in groundwater recharge, and in streamflow. Climatic variations also cause changes in patterns of erosion, of which spectacular consequences can be observed in arid areas.

Hydrologic benchmarks are basins and associated stations established to provide simple measures of time trends in the secular march of hydrologic events unaffected by the works of man. Beyond simple measurements, however, they provide the means for more sophisticated uses such as direct comparison with other records. For example, records of streamflow at a regular gauging station may show a downward trend relative to flow at a nearby hydrologic benchmark. In suitable circumstances, this would be direct evidence of streamflow depletion.

Hydrologic benchmarks would help unravel the interrelations among climatic and hydrologic variables with confidence that the results are not biased by effects of human activity. The interrelations thus demonstrated could provide the base or datum for distinguishing natural from artificial phenomena elsewhere."

This quotation illustrates the concept behind benchmark basins for use in land-use studies. Their use is not sufficiently widespread or well-established to give much indication of their value at this time.

(vi) Vigil Basins

The following is quoted from the Report of the 1st Session of the Co-ordinating Council of the I.H.D. :-

"The purpose of (the Vigil) network is to establish stations and make observations generally similar to those established for the benchmark networks, but with no attempt either to protect the station from artificial changes or to deliberately introduce special changes. Vigil basins may be regarded as a special type of representative basin.

The purpose of the vigil basins is to collect data that will clarify relations between man, the land and the hydrological cycle. The network will include areas, therefore, that are subject to such uses as farming, grazing, deforestation, afforestation, community development, and other activities of man."

The Co-ordinating Council of the I.H.D. recognised Vigil Basins as a special type of catchment for data collection, but did not recommend special attention to this form of catchment during the I.H.D.

Even with the description given, the concept and exact purpose of Vigil Basins are somewhat vague, and their relation to benchmark and representative basins also cloudy. The proposals given by Slaymaker and Chorley (ref. 47) for establishment of a Vigil Network in Great Britain give the impression that these basins are intended wholly for geomorphological studies, but this may have been just the special interest of these authors.

Vigil Basins appear to be midway in size between unit source areas and representative basins. They are about the same size as catchments generally used in experimental studies, but are an observational type of catchment. They complete a series, arranged in order of size, of plots - unit source areas - vigil basins - representative basins - general streamgauging networks.

7.4 COLLECTION OF DATA - EXPERIMENTAL METHODS

With experimental methods, as distinct from the observational methods described earlier, the experimenter observes a catchment during a calibration period until he is satisfied that he is able to determine the "normal" response of the catchment under given conditions of rainfall and evaporation, either by comparison with the behaviour of another catchment nearby or from some relationship with rainfall, evaporation, etc., established during the calibration period.

The experimental catchment is then treated in the required manner and the runoff or sediment yield observed after treatment is compared with estimates of the normal or without-treatment behaviour of the catchment obtained from the earlier comparisons or calibrations.

The basic experimental methods used are -

(i) Calibration of Single Catchment
(ii) Paired Catchments
(iii) Multiple Catchment experiments.

(i) Calibration method

This method is also referred to as "Before and After" technique, "Single Basin" technique and by some other titles. Essentially, a single catchment is calibrated for a number of years until its behaviour can be predicted from its past performances. A treatment is imposed and its effect is measured in terms of the deviation from the expected behaviour.

Success or failure of this method depends wholly on the ability to predict the behaviour of the catchment from climatic variables, usually rainfall and evaporation. The two approaches to relating runoff to climatic variables are by linear regression (for example, see Reigner, (ref. 39) or by use of a catchment model.

Reigner describes the single watershed approach as -

"..less costly because no control is involved, and the analysis is more informative because it relates streamflow to the factors that influence it rather than to streamflow from another watershed only. Its principle disadvantage is its complexity; considerably more tabulation and analysis of data are required than with the control watershed system."

However, the single watershed approach is not well regarded generally. Sharp, Owen and Gibbs (ref. 46) conclude "..it is not believed this method of testing effects of land use and treatment changes on water yield is either logical or practical, hence, although it has been tried, is not being used by this project."

(ii) Paired Catchments

This method involves the use of an untreated control catchment (sometimes more than one) in conjunction with the experimental catchment which is to be treated. This method is also called "Comparative Basins" technique, "Control Watershed" method, etc., but all names refer to the same concept and method.

Two catchments are selected for their similarity in size, shape, topography, plant cover, land-use, climate, and general location. First, they are calibrated for a period of years to establish the response of each to a variety of storm conditions. The period of calibration is long enough that the behaviour of one can be predicted from the behaviour of the other. Criteria and methods for determining the required length of calibration have been proposed by Wilm (ref. 57) Kovner and Evans, (ref. 34) Bethlahmy (ref. 9), and Reinhart (ref. 40). The period appears to range from about 3 to 10 years.

Following the calibration, a treatment is applied to one catchment while the other is left as a control. The effects of the treatment are measured as departures from the predicted behaviour of the catchment. The predictions of expected behaviour are based on the control catchment, but may be supported by predictions based on the period of calibration. If the climatic conditions are the same for the treatment and calibration periods, and the characteristics of the control catchment have remained unaltered, then changes in the characteristics of streamflow or sediment yield are attributed to the treatment.

This technique was first used in the Wagon Wheel Gap study of 1911 (Bates and Henry, (ref. 8)). Hibbert, (ref. 30) lists 32 paired-catchment studies of the effect of forest treatments on water yield.

The most comprehensive study of this method has been made by Sharp, Owen and Gibbs (ref. 46). They found that the ratio of flow on one catchment to flow on another was not constant during periods of calibration before any treatments had been applied. They reported that "the reactions of small watersheds...are so erratic that direct comparisons are not safe".

Ivanov and Romanov (ref. 32) also give examples to show that the use of comparisons between catchments can be meaningless. They used various pairs of catchments to illustrate the relative evaporation rates from swamps and swampless areas. Three pairs of catchments were used in the example and, according to the authors, "each pair of comparative basins is selected within a homogeneous physiographical region which is homogeneous not only in climatic conditions but also in relief, geologic structure and some other characteristics. The selection was performed on the basis of usual qualitative areal descriptions without any quantitative measures of relief and other characteristics."

Comparison of the second pair of catchments showed that normal annual evaporation from swamps is greater than from swampless areas, comparison of the third pair of catchments showed that it is less, while comparison of the first pair showed that normal annual evaporation from swamps was a negative amount.

(iii) Multiple Catchment Experiments

Wicht (ref. 56) describes multiple catchment experiments in South Africa designed to overcome the deficiencies of paired catchment experiments. These are afforestation experiments on a group of 6 catchments, designed to compare the hydrological effects of deliberate controlled burning in spring, summer and autumn on 4 to 12-year cycles, and indefinite protection of the scrub.

An integrated pattern of treatments is applied to the complex of watersheds, in which the components are closely comparable in geology, topography, and initial vegetal cover, and simultaneously subject to the same or related uncontrolled, extraneous, climatic influences. Related treatments on related watersheds are expected to produce related effects.

The experiments are designed for a major rotation cycle of 40 years and, on the 6 watersheds included, an 8-year secondary planting-cycle permits the progressive development of a complete series of age classes. The burning experiments are designed to include indefinite protection with which burning can be compared.

The comparison of identically treated watersheds and of diversely treated watersheds with two or more under the original treatment will be used to test whether discharge relationships have changes due to influences other than that of the treatment. The treatments are replicated and the results checked by repeated comparison of different watersheds variously treated.

Striffler (ref. 51) describes experimental work on forested catchments in the central and southern United States where the effects of disturbances, such as roading and strip mining, on water yield and water quality, is evaluated by the multiple catchment technique. Data from a large number of catchments are analysed statistically to determine the influence of the disturbances.

In New Zealand, Yates (ref. 59) describes a series of multiple catchment experiments (called "comparative catchment studies") designed to assess the effects of grazing, oversowing and topdressing, and cultivation and conservation structures (such as pasture furrows and graded banks) on runoff and soil loss. These experiments were planned by the Department of Agriculture, to be undertaken on groups of catchments at Makara and Moutere. At Makara, eight catchments were to be combined in a 2 x 2 factorial experiment, and similar experiments were proposed for the 16 catchments at Moutere.

These examples portend the development of more complex experimental methods in hydrology, beyond the traditional calibration and paired catchment techniques.

7.5 ANALYSIS OF DATA

The variables used as criteria to illustrate the effects of land-use changes are numerous. For example, a few of the variables used in simple comparison studies of runoff (neglecting the many variables in catchment models, and sediment yield variables) are:-

volume of runoff

peak rate of runoff

coefficients of runoff

seasonal distribution of runoff

half-flow time

flow duration distribution

groundwater recession constant

There are also ratios of runoff from one catchment to runoff from control catchments, residuals of rainfall minus runoff, etc. To simplify the profusion of variables used as these criteria, the following classification is proposed for methods of analysis:-

1. Statistical

   (i) Graphical Methods
   (ii) Single variable analysis
   (iii) Multi-variable analysis

2. Physical

   (i) Mathematical models
   (ii) Physical models
   (iii) Analogue models

Statistical methods treat the data as abstract variables without concern for cause and effect relationships. The emphasis is on testing the significance of differences between data obtained after change in land use from data obtained before the change. The major abuse of statistical methods occurs when attempts are made to use the results from an arbitrarily selected model (e.g. multiple linear regression) from which wild speculations about physical behaviour of the variates are made.

Physical methods, on the other hand, begin from known or postulated cause and effect relationships and are generally used to demonstrate that the proposed physical relationships reproduce observed hydrological behaviour to a satisfactory degree. Statistical and physical methods are described in more detail in the following sections.

7.6 ANALYSIS OF DATA - STATISTICAL METHODS

(i) Graphical

The use of graphical methods of analysis such as double-mass plots (plotting cumulative runoff from one catchment against cumulative runoff from another catchment) is common in land use studies. Graphs are used both to find and to illustrate the changes thought to be caused by the change in land use.

Graphical methods have a place in preliminary analyses and for illustration of results after more comprehensive analyses. However, graphical methods only supplement the final statistical analysis of data and are not an alternative. It is unfortunate that graphical methods are often proposed as the sole analysis of data that may have taken 10 or more years to collect.

Most graphical methods have a statistical equivalent from which numerical values can be given to the variations detected on a graph. This can be illustrated by considering the common graphical method of plotting cumulative runoff from one catchment against cumulative runoff from a second catchment. This method is usually associated with paired catchment experiments and involves two assumptions:-

(a) the ratio of runoff from one catchment to runoff from the second catchment is relatively constant and so the cumulative plotting results in a relatively straight line.

(b) following treatment of one catchment (or change in its land use) the ratio of runoff will still be relatively constant but at a different value, the difference appearing as a different slope on the graph, and being due to the treatment.

In reality, the runoff ratio before treatment is not a single value but will have a distribution of values about a mean value. After treatment, there will still be a scatter or distribution of values of the runoff ratio, but the hypothesis to be tested is that the mean has changed to a different value.

This resolves into a simple exercise in statistics. There are two groups of values for the runoff ratio (before treatment and after treatment) and we can test the probability that both groups are drawn from the same population, i.e. the difference between them is due to chance fluctuation and not conclusively attributable to the change in land use. If the student's test shows that the probability of the two groups being drawn from the same population is very small, then the hypothesis that the difference in mean value is due to the treatment is substantiated. The difference between the means of the two groups of value may then be accepted as the difference produced by the treatment or change in land-use.

However, fluctuations in runoff due to differences in rainfall can be significant, and statistical checking of the homogeneity of the climate before and after treatment should be made to avoid introduction of such errors. Unfortunately, there is no established methodology for analyses such as these.

Another method of graphical analysis which has been used is to plot flow duration curves for both before and after treatment and to attribute differences in the curves to the treatment. This also ignores natural variations in flow durations on untreated catchments and can allow natural variations to be interpreted as being due to the applied treatment. A conversion to a statistical equivalent may be made by examining the differences between the before treatment distribution and the after treatment distribution using the chi-square test of significance.

(ii) Single Variable Analysis

The most important aspect of data analysis is to take account of natural variations and to ensure that other variations, which are to be attributed to change in land use, are significantly different from the natural fluctuations. Not all of the variables which are encountered in these studies are constant from storm to storm or from year to year. Volumes and peak rates of runoff, coefficients of runoff and distribution of runoff throughout the year, etc., all show differences from one period of record to another. It is human nature that the fluctuations which veer towards the direction we hope for are accepted as proof of our hypothesis while fluctuations which veer away from the desired directions are discarded as errors in measurement.

Simple statistical techniques are available to help distinguish variations caused by changes in land use from natural variations in the variable being analysed. The two techniques which are most useful for the tests of significance needed in these studies are the Student's t test and the Chi-square test.

In records collected over a number of years, a variable such as the date when half of the yearly flow has passed (half-flow date) will have a mean value and a standard deviation of the values. Following a change in land use, a new mean value is observed. The Student's t test will give a test of significance of the difference in the mean values. Half-flow date was proposed by Court (ref. 18) for studying possible changes in streamflow regime caused by watershed management practices, especially vegetational manipulation aimed at increasing snowpack and delaying snow-melt.

The problem of significant differences in distributions such as change in a flow duration distribution, is more readily examined using the Chi-square test. Changes in flow duration curves have been used by Reinhart (ref. 40) and others.

Knisel (ref. 35) and Brown (ref. 16) used the slope of the recession curve as an indicator variable, while Schneider (ref. 45) uses a low flow index defined as the "average annual minimum daily flow". There is a multitude of coefficients based on the ratio of runoff to rainfall; for example, Dunin (ref. 25) uses 3 yield coefficients - on an annual basis, on a storm basis and on rate of flow basis - in analysis of a paired-catchment experiment in Victoria.

Hewlett and Hibbert (ref. 29) define two response factors which describe the ratio of surface runoff to total runoff (surface runoff plus groundwater flow) and the ratio of surface runoff to precipitation. These measures are meant to indicate the effects of forests in ameliorating flood flows from a catchment.

These examples may give some idea of the range of variables used as indicators, either of the effects of a change in land use or of the difference between catchments having different characteristics. There is a need for a more detailed review of these variables than is given here and of some sorting and classifying.

(iii) Multivariable Analysis

Multivariable analysis is most common in analysis of observational experiments. Data are recorded from a number of variables, and the data are analysed to determine what correlations exist among the variables. An illustration is the equation used by Musgrave (ref. 37) for predicting soil loss:-

$$E = I.R.S.^{1.35} . L^{0.35} . P_{30}^{1.75}$$

where

E = soil loss in acre inches

I = inherent erodibility of soil in inches

R = a cover factor

S = degree of slope in percent

L = length of slope in feet

P_{30} = maximum 30 minute rainfall amount for a two year frequency, in inches.

The most popular method used for multivariable analysis is linear regression. It has increased in popularity since the introduction of digital computers, undoubtedly due to the prepared regression programmes which are now available at most computer installations and the case with which they can be used.

Multiple non-linear regression is not common except for logarithmic transformation of a linear regression, which results in equations of the type illustrated in the soil loss equation above. Graphical multi-variable non-linear correlations are not common but graphical methods are flexible to use. The accuracy obtainable with graphical methods is frequently equal to the accuracy of the data used.

Multiple regressions are useful in deriving prediction equations where the value of one variable e.g. soil loss, can be predicted from values of other variables e.g. slope, cover etc., based on past relationships of the variables. However, much confusion arises when attempts are made to interpret these prediction equations as cause and effect relationships.

The difference between prediction equations and causal relationships becomes clouded in land use hydrology where the physical process is complex and not well understood. A recent example (Taylor, ref. 52) illustrates the absurd misinterpretations that can occur with indiscriminate use of multiple linear regression. By attempting to correlate mean annual discharge in cusecs with mean annual rainfall and catchment area as independent variables, Taylor found that rainfall was not a significant factor in causing runoff. To quote:-

"Rainfall emerges as a significant factor only when the effect of area is incorporated in the dependent variable as a runoff/area ratio; the mean annual rainfall then becomes of prime importance. To a large extent, however, the effects of catchment size overrule the effects of local climatic variations."

A little reasoning in advance should have dictated that the volume of runoff should have been correlated with the volume of input, i.e. the product of rainfall and area, and not with rainfall and area as independent factors. Misuses of multiple linear regression such as this have resulted in many hydrologists discarding the method altogether.

In an endeavour to find a statistical method by which causal relationships might be established, some hydrologist have turned to factor analysis (Snyder, ref. 48, Wong, ref. 58, Eiselstein, ref. 26). In multiple regression, the contribution of a number of predictor variables to the variance of the dependent variable is expressed in the prediction equation. In factor analysis, principle components are found which describe the variance of all of the variables. The principle components or factors are the eigenvectors of the correlation matrix of the variables.

Unfortunately, there is no direct physical significance of the eigenvectors. To quote from Eiselstein:-

"The interpretation of the eigenvectors is somewhat subjective and consists of determining which of the original independent variables are primary contributors to each eigenvector and from this information deciding which quantities of variance each eigenvector is mainly concerned with."

It is this subjective interpretation that is the major weakness of factor analysis. This method, therefore, offers no more information on physical relationships than does multiple linear regression. Both methods can establish that there is some correlation between the variables but neither can determine whether this is spurious or causal.

7.7 ANALYSIS OF DATA - MODELS OF PHYSICAL PROCESSES

The difference between models of physical processes and the previously described statistical methods of analysis is one of the most important distinctions in modern hydrological analysis. Catchment models are deterministic instead of probabilistic, parametric instead of stochastic, and are based on a specified structure of physical processes rather than on a manipulation of independent and abstract data sets.

Models of physical processes range from hydraulic models, or scale models, of watersheds using artificial rainfall, to mathematical models. The classifications and terminology used are neither simple nor uniform. Many different classifications of deterministic models have been proposed.

Nemec and Moudry (refs. 60, 61) proposed that there are three types of modelling of the surface runoff process - physical models, analogue models, and mathematical models. Physical models are generally laboratory models of catchments, usually involving dimensional analysis to obtain similitude between model and prototype. The model prepared by Chery (refs. 62, 63) is one of the best examples of this type. Other studies are by Mamisao (ref. 64), Chow (ref. 65), and Amorocho (ref. 66).

Analogue models are based on the use of different physical phenomena between prototype and model, but whose mathematical description is the same. The best example of an analogue model of a whole catchment runoff system is that by Riley and others (refs. 67, 68). Their model is a resistance-capacitance network which simulates the rainfall-runoff processes of a catchment. Analogues have been widely used in groundwater studies, flood routing, and other applications (Shen, ref. 69).

Mathematical models are a complete abstraction of the physical process into mathematical form. These models may be of a single component of the hydrological process, e.g. infiltration or evapotranspiration, or of a whole catchment system. The most widely-used mathematical catchment models to date are the Stanford Model in the U.S.A. (refs. 19-22) and the Boughton model in Australia (refs. 10, 11, 15).

Dooge (ref. 70) proposed a different classification of simulation methods used in rainfall-runoff analysis. He proposed three types:-

(1) direct simulation (scale models, analogues etc.)

(2) semi-direct simulation (network analysers, Hele-Shaw models, etc.)

(3) indirect simulation (desk calculators, digital computers, etc.).

These three types correspond closely with the physical, analogue, and mathematical models described by Nemec and Moudry.

Amorocho and Hart (ref. 71) further divide laboratory physical models into two types - model catchments and laboratory prototype systems - and the latter type is again subdivided into "hydromechanic prototypes", which encompass the many devices used to make detailed studies of specific hydraulic mechanisms, and "prediction analysis prototypes" which are used to provide laboratory data for the test of methods for the mathematical analysis of systems. Chery (ref. 72) discusses these methods and their uses. Their principal application is to the study of hydrograph shape, with little use for the water balance aspects which determine catchment yield.

Only a few of the models mentioned in this section have been used for the purpose of evaluating how changes in land use affect runoff or groundwater recharge. Narayana and Riley (ref. 73) used the electronic analogue catchment model developed at the Water Research Laboratory, Utah State University, for study of the effects of urban development on the hydrologic regime. James (ref. 74) also studied the effects of urban development on flood peaks, the model used being the Stanford mathematical catchment model. Generally, most models of physical processes have been used for study of basic rainfall-runoff relationships, rather than the effects of any change in land use.

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CHAPTER 8

EFFECT OF LAND MANAGEMENT ON COMPONENTS OF THE HYDROLOGICAL CYCLE

8.1 INTRODUCTION

The chapters in Part I of this report contain the results of many empirical studies which demonstrate effects on water resources by change in land use and land management. The results of such studies are useful in delineating that certain effects occur, but are rarely suitable for producing general relationships or for extrapolation to other areas and other circumstances.

The only method which appears suitable for obtaining results which can be used in widely different circumstances and localities is to deal with the disposition of precipitation in each catchment by a detailed water balance and to consider the effects of any change in land use on individual components of the water balance. While the number of such studies to date has been few, this method has attracted increasing interest in recent years, particularly since the advent of high-speed digital computers which makes it possible to undertake the large amount of calculation involved in daily and even hourly water balances.

Because of the relative newness of these methods, there is no established methodology as, for example, in paired catchment experiments. Individual workers tend to use methods appropriate to the area of their own interest, and there is only limited similarity between, say, studies of change in land use affecting saline groundwaters in the wheat belt of Western Australia and studies of snow-depth and snowmelt in mountain areas.

Only a few publications include any description of the land phase of the hydrologic process and the individual components that may be affected by change in land use. Downes (ref. 1) suggests that there are variants of the basic water balance equations for broadly differing regions, namely, arid areas where, on an annual basis, the precipitation is small in relation to potential evaporation and transpiration; humid areas where the reverse situation holds; and the intermediate areas where the precipitation about balances the potential evapotranspiration.

Downes then discusses the effects of land use on individual components of the water balance in these areas, and lists the components as precipitation, evaporation, transpiration, surface runoff, and infiltration.

Colman (ref. 2) in a description of the influence of vegetation on hydrologic processes lists interception, infiltration, soil moisture storage and drainage, evaporation and transpiration, and surface flow, in addition to erosion and deposition and snow accumulation and melt.

Storey, Hobba, and Rosa (ref. 3) in a description of the hydrology of forest lands and rangelands list the components affected by vegetation as interception, infiltration, evapotranspiration, soil moisture storage and drainage, overland flow, and snowmelt, in addition to erosion and sedimentation. Chapman (ref. 4) lists interception by vegetation, evapotranspiration, gain and loss of soil water, surface detention, overland flow, stream channel flow, and groundwater recharge and discharge. Philip (ref. 5) gives a description of the physical processes involved in the infiltration of water into soil and evaporation from free water and soil surfaces but does not cover the whole runoff process.

Different components of the hydrologic process are involved depending on whether the effects studied are effects on volume of runoff, rates of flow, water quality, or erosion. For the purpose of brevity in this report, discussion here will be restricted to effects on volume and rates of runoff. Some consideration is given to effects on water quality in the following chapter on mathematical models.

The major components of the water balance involved in the effects of land use on volume and rates of runoff can be considered under the following headings:-

Effects on precipitation

Effects on interception

Effects on depression and detention storages

Effects on infiltration

Effects on soil moisture storage

Effects on evapotranspiration.

Changes in the amount and rates of surface runoff and groundwater recharge and discharge are considered to be end products of the above effects.

8.2 PRECIPITATION

The notion that forests increase water resources by inducing more rain to fall is a hardy myth that is still prevalent among uninformed lay persons. Because forests occur frequently in high rainfall areas, the cause and effect relationship is often confused and distorted to support the idea that it is the forests causing the rain rather than the reverse. There is little evidence to suggest that forests increase rainfall except in some special circumstances in alpine areas.

There is some evidence to suggest that precipitation in alpine areas can be modified, although the effects are small in relation to natural precipitation. The means by which precipitation might be modified seem to be that trees may increase the catch of rain in moist cloudy environments by straining out or condensing mist and fine rain, and that snowfall and rate of snowmelt might be modified by creating small clearings in a forest or constructing artificial wind-breaks.

Costin (refs. 6, 7) measured precipitation in the open and under trees in the Guthega catchment in the Snowy Mountains in New South Wales at 4 sites between 4000 and 6000 feet. The catch was significantly greater under the trees during windy periods of mist and fine rain, particularly at the higher elevations. At freezing temperatures, rime from moving fog and cloud collected on the trees in large amounts. It was concluded that the timbered areas would probably collect an additional 2 to 5 inches of water per annum compared with treeless areas.

Costin also measured snow water content in a range of natural and artificial clearings from continuous snow gum to large open areas. Smaller clearings accumulated substantially more snow than under the trees, and more than in the larger clearings and open areas. The optimum clearing was about 4 to 10 times the height of surrounding trees depending on exposure. The deeper snowpacks persisted longer into the spring before melting.

The possibilities of managing snowpacks have attracted much interest from foresters, particularly in the U.S.A. Lull and Pierce (ref. 8) review prospects for affecting the quantity and timing of water yield through snowpack management. Martinelli (ref. 9) suggests operational procedures that may have some chance of success - intentional avalanching to store snow in high-elevation shaded valleys; reshaping natural terrain features to improve their snow trapping efficiency; construction of snow fences or other barriers to increase the amount of snow in areas of natural accumulation; and control of snowmelt by the addition of materials to the snow surface. Martinelli reports that snowfences in the Rocky Mountains in Colorado increased natural snow accumulation by one acre-foot of water per 100 to 125 feet of fence. Tabler (ref. 13) gives an excellent summary of the evaluation of increased snow accumulation by snowfences.

Hoover and Leaf (ref. 10) report more snow in cleared areas than under trees on a 714 acre catchment from which timber had been removed from 39% of the area in a series of strips. However, these authors point out that total snow catch of the whole catchment remained the same as before clearing the strips. They attribute the recorded increase in runoff to a redistribution of the snow rather than to any increase in total catch.

Other reports such as those by Eschner and Satterlund (refs. 11, 12) record observations of different snow catches under different plant covers, the effects of introducing clearings on snow catch, and the effects of both cover and clearings on rates of snowmelt and thaw of frozen ground. However, most of the available evidence is inadequate for producing any generalised relationship or prediction equation. This particular aspect of land management has not progressed far beyond the stage of observing that trees can influence the deposition of snow and rates of snowmelt, and may increase the total catch of precipitation in special circumstances.

8.3 INTERCEPTION.

When rain commences over a dense forest, there is an interval while the foliage of the canopy is being wetted before any rainfall comes through to the ground. Early thought in hydrology was that this intercepted water was "lost" by not being available to replenish soil moisture or produce runoff. Later opinion was that the intercepted water was not a true loss as the evaporation of this water would tend to reduce the amount of water transpired from the vegetation by a similar amount, and so reduce any overall effect of the water balance.

In recent years, the concept of interception capacity has become complex, involving litter interception as well as canopy interception, and the redistribution of rain by branch drip and stemflow as well as questions of the difference in rates of evaporation of water from interception storage and soil moisture. The subject is of particular interest where conversion from trees to crops or grass may produce change in interception capacity with subsequent change in water balance.

Zinke (ref. 14) traces the development of interception concepts by a review of the complex terminology which is now in use. The following, from his review, indicates the complexity of the process and the detail in which it has been studied.

INTERCEPTION: according to Horton (ref. 15) total interception equals leaf storage capacity plus evaporation loss during the storm. Hamilton and Rowe (ref. 16) have considered interception to be the process in which rainfall is caught by the vegetative canopy and redistributed as throughfall, stemflow, absorption, and evaporation from the vegetation. Hamilton and Rowe also give the following definitions:

THROUGHFALL: that portion of the rainfall which reaches the ground directly through the vegetative canopy and through openings and as drip from leaves, twigs, and stems.

STEMFLOW: that portion of the rainfall which having been intercepted by the canopy reaches the ground by running down the stems.

INTERCEPTION LOSS: the portion of the precipitation retained by the aerial portion of the vegetation and is either absorbed by it or is returned to the atmosphere by evaporation. In the opinion of some investigators, drip from the stem of rough barked trees should be included in stemflow (Voigt, ref. 17).

GROSS RAINFALL: actually measured rainfall in the open or above the vegetative canopy.

NET RAINFALL: the quantity of rainfall which actually reaches the ground, the sum of throughfall and stemflow.

STORAGE AREA: the surface area of leaves, twigs, branches, and stems that can retain water against gravity.

STORAGE CAPACITY: was defined by Horton (ref. 15) as the depth of water on the projected area covered by the plant which can be stored or detained on the plant surface in still air.

As a result of detailed studies on single plants, Grah and Wilson (ref. 18) used the following terms:

SURFACE DETENTION: water retained on the surfaces of leaves and stems. They felt that this had three components as follows:-

MAXIMUM SURFACE DETENTION: that occurring during the shower when the plant surfaces are unable to hold any more water.

SURFACE DETENTION AFTER DRIP: that occurring in still air after rain has ceased and the excess has drained from the plant (upper extreme in the field).

SURFACE DETENTION AFTER SHAKE: that occurring after the excess has drained and the plant has been shaken to simulate maximum air movement. Usually the lower extreme in the field after strong wind.

Further subdivision of the components are then made into:

TRANSITORY STORAGE: maximum detention minus surface detention after drip.

CONDITIONAL STORAGE: surface detention after drip minus surface detention after shake.

RESIDUAL STORAGE: amount of water retained after drip and shake.

Each of these components amounted to about one-third of the maximum surface detention.

Because of problems arising as to whether interception is a true loss to the soil-vegetation system, Burgy and Pomeroy (ref. 19) have chosen to subdivide interception loss into:

GROSS INTERCEPTION LOSS: that portion of the rainfall that is retained on the aerial portion of the vegetation.

NET INTERCEPTION LOSS: that portion of the rainfall retained on the aerial portion of the vegetation that has no net effect on the soil water consumption of the plant (assumed to be the only true loss by these authors).

The storage and evaporation of water by leaf litter layers in a forest has been less frequently studied. Rowe (ref. 20) and more recently Helvey (ref. 21) and Helvey and Patric (ref. 22) have chosen to include evaporation losses from the leaf litter layers of the forest floor as interception loss, and they have used the following terms:

TOTAL INTERCEPTION LOSS: rainfall per storm retained by the canopy and litter and evaporated without adding to moisture in the mineral soil.

NET RAINFALL: water that enters the mineral soil after penetrating the forest canopy and litter, sometimes called "effective rainfall".

CANOPY INTERCEPTION LOSS: rainfall retained on standing vegetation and evaporated without dripping off or running down the stems.

LITTER INTERCEPTION LOSS: rainfall retained on the litter layer and evaporated without adding to moisture in the underlying mineral soil.

These definitions reflect some of the problems which are inherent in the study of interception. To avoid an abundance of effects from the profusion of terms, which could confuse rather than clarify the effect of interception on the water balance, the discussion in this report can be limited to the answering of two questions:

(i) what effect does change in land use have on interception capacity?

(ii) what effect does change in interception capacity have on the water balance?

The additional water storage capacity of a catchment created by interception capacity is generally small in relation to soil moisture capacity. Zinke (ref. 14) has summarised interception storage data in American literature (refs. 15, 16, 18-31 incl.). About 50% of the values given in his summary are 0.05 inches or less, about 30% in the range 0.05 - 0.10 inches, and 20% above 0.10 inches (excluding snow interception values). These values were for canopy interception capacities, not including litter interception, and he concluded:

"The storages indicated that one would not be greatly in error to estimate about 1.3 mm (0.05 in.) storage capacities for rain for most grasses, shrubs, and trees; and 3.8 mm (0.15 in.) for snow for trees."

In a previous American study, Helvey and Patric (ref. 22) summarised all available reports of rainfall interception by hardwood forests in the eastern U.S.A. Their results showed that throughfall and stemflow varied over a surprisingly narrow range in the studies reviewed. Using regression analysis, these authors produced the following equations which are the most useable to date for estimating interception losses from storm rainfall:

	Summer	Winter
Throughfall	T = 0.901.P - 0.031	T = 0.914.P - 0.015
Stemflow	S = 0.041.P - 0.005	S = 0.062.P - 0.005

where P = storm rainfall
T = throughfall
S = stemflow
(all values in inches)

The following equations were also given for estimating seasonal values of throughfall, streamflow, litter interception loss, and total interception loss, from total seasonal rainfall (Pt), and number of storms (n).

	Growing Season	Dormant Season
Throughfall	T = 0.901.Pt - 0.031.n	T = 0.914.Pt - 0.015.n
Stemflow	S = 0.041.Pt - 0.005.n	S = 0.062.Pt - 0.005.n
Litter interception loss	L = 0.025.Pt	L = 0.035.Pt
Net rainfall	R = 0.917.Pt - 0.036.n	R = 0.941.Pt - 0.020.n
Interception	I = 0.083.Pt + 0.036.n	I = 0.059.Pt + 0.020.n

(all values in inches)

In Australia, Jones (ref. 32) reviewed available data for estimating interception storage capacity values to be used in the Boughton catchment model (see Chapter 3) for estimating the yield of ungauged catchments. The objective in Jones' study was to provide a basis for estimating the storage capacities of parameters in the model from field measurements, rather than adjust the parameter values to make calculated runoff agree as well as possible with recorded flows.

Jones set out the available information from the studies that he reviewed (refs. 15, 18, 19, 23, 24, 26, 33-40 inclusive) into 4 groups:

i. field studies of interception losses
ii. theoretical calculations based on wetted surface area.
iii. laboratory measurements of the moisture retained by sprinkled vegetation.
iv. general range of values quoted in the literature.

He summarised the median values of interception capacities of trees, grass, and crops, from all methods and sources of information as follows:

Cover	Median Value interception capacity.
Trees	0.0325 inches
Grass - 2 feet	0.0495 "
2 to 6 feet	0.0200 "
6 feet	0.0575 "
Crops	0.0385 "

Jones concluded that "a consistent difference in storage capacity for trees, crops, and grass of various heights was not evident."

While this review and the others cited above show little difference in the interception capacities of trees and grass, there is some evidence of a difference between the rates of evaporation of intercepted water from the surface of vegetation and the corresponding potential transpiration rate from the leaves under the same conditions.

Rutter (ref. 41) reports an analysis of evaporation from a stand of Pinus sylvestris in Southern England in which the rate of evaporation of intercepted water was, on average, about 4 times as great as the transpiration rate in the same conditions. Rutter found that the differences were due to differences in the mean resistances to the diffusion of water vapour from wet leaves and from transpiring leaves with dry surfaces. It was possible to explain the observed differences satisfactorily using different values for the resistance to vapour transport in the Penman evaporation equation (ref. 42).

The calculated and observed rates of evaporation of intercepted water were of the order of 1 to 3 mm/day in winter and 7 to 10 mm/day in summer and they exceeded the equivalent intensity of net radiation considerably. Rutter concluded that the additional energy required was obtained from the air. Evidence for this was the difference between wet leaves, found to be 0.3° to 1.0°C cooler than the surrounding air, and transpiring leaves, found to be only 0 to 0.1°C cooler than the air.

Generally, the order of magnitude of interception capacity values are small compared with soil moisture storage capacities. Soil moisture capacity is about 2 inches of water per foot depth of soil for a wide range of soil types. Temporary capacity between field capacity and saturation adds more to the storage capacity during storms. Even surface storage capacities which are used in mathematical catchment models to simulate the initial loss potential of catchments have values in the order of 1.0 inch to 5.0 inches.

The conclusions which can be drawn from the available evidence are as follows:-

(i) the principal effect of interception on the water balance is from an accelerated rate of evaporation loss of intercepted water following a storm at a rate higher than the potential evapotranspiration rate.

(ii) there does not appear to be any consistent differences in interception capacity among trees, grass and crops.

(iii) interception capacities are very small compared with total moisture storage capacities of catchments, being in the order of 0.05 inches.

8.4 DEPRESSION AND DETENTION STORAGES

8.4.1 Introduction

There is an interval between the commencement of rainfall on a catchment and the start of surface runoff at the outlet from the catchment. The amount of rainfall needed to "wet" the catchment enough to produce surface runoff is usually called "initial loss" (see ref. 43), and the value can be as high as 5 to 6 inches on large catchments.

The storage capacity of initial loss appears to be composed of interception storage, depression and detention storage, and the high initial abstractions of infiltration loss. Infiltration is dealt with in the next section; discussion in this section is restricted to the effects of change in land use on depression and detention storages and how this affects volumes and rates of runoff.

Linsley, Kohler, and Paulhus (ref. 44) give a description of surface retention as follows:

"Much of the rain falling during the first part of a storm is stored on the vegetal cover as 'interception' and in surface puddles as 'depression storage'. As rain continues, the soil surface becomes covered with a film of water, known as 'surface detention', and flow begins downslope towards an established surface channel. En route to a channel, the water is designated as 'overland flow' and, upon entering a channel, it becomes 'surface runoff' ".

Depression storage is not directly measurable and even detention storage is usually derived from hydrograph analysis rather than from observation. Moreover, the phenomena are complicated by variation in the storage capacities over the area of a catchment. Surface runoff can and usually does commence from one portion of a catchment before the interception and depression storages on other parts are satisfied. Also, on catchments where flow is intermittent or ephemeral, transmission losses can occur in stream channels, and surface runoff from the upper parts of a catchment may not show up at a gauging station further downstream.

From the information available in the literature, it appears that the following components constitute the major parts of depression and detention storage on natural catchments:

Depression Storage:

- small depression in the surface of the ground
- transmission loss in stream channels
- storage deficits and losses in dams on the catchment
- natural swamps and areas of blind or restricted drainage

Detention Storage:

- overland flow film
- channel storage
- flood control dams
- swamps with slow but free drainage.

These are described in detail with references to reported studies of each in the following sections.

8.4.2 Depression Storage

(i) Surface Depression Storage:

Very little data has been accumulated on the values of surface depression storage, and consequently there is little information about the influence of change in land use on such values. Hicks (ref. 45) used depression storage losses of 0.10 in., 0.15 in., and 0.20 in. respectively for clay, loam, and sand, based on an analysis of periods of high rates of rainfall and runoff. Tholin and Keifer (ref. 46) used depression storages of 1/4 inch on pervious areas and 1/16 inch on paved areas in a study of urban runoff in the City of Chicago.

In Australia, Bell (ref. 47) measured puddle depths at Lidsdale State Forest in New South Wales after a prolonged flood-producing storm in June 1964 when the ground was close to saturation, all depressions were filled, and overland flow had almost ceased. Traverses were made through mature pine forest, through eucalyptus, and a grassed firebreak with soundings of depression depth every 6 feet. Over 100 observations were made in each traverse and these were averaged and summarised as follows:

Slope	Mature Pine	Eucalyptus	Firebreak
less than 5%	0.3 in.	0.2 in.	0.4 in.
5% - 15%	0.2 in.	0.1 in.	0.3 in.
over 15%	0.1 in.	0.05 in.	0.2 in.

Bell reported that "the differences between vegetation are caused by the effects of the litter which appeared to be more significant than irregularities in the soil surface."

A review by Boughton (ref. 48) of quantitative measures of catchment characteristics produced only one measure adaptable for direct measurement of depression storage. This was a measure of "random roughness" of the microtopography of the soil surface by Burwell and others (refs. 49, 50). These authors give some guide of how cultivation and other management practices affect the soil surface in terms of their measure of roughness.

Doty and Wiersma (refs. 51, 52) made measurements of the micro-profiles of cultivated land and derived estimates of the water storage capacity on different slopes. They compared the surface storage capacities of different methods of cultivation and found surface depression storage values ranging from 1 to 3 inches.

A principal objective of many land treatment measures is to artificially increase the capacity of surface depression storage by construction of absorption banks and terraces. The magnitude of this increase appears to be about 2 inches on moderately sloping ground to about 3 inches on fairly flat ground.

(ii) Transmission Loss in Stream Channels.

Some substantial abstractions from runoff as flow moves down a stream channel have been recorded. Laurenson (ref. 53) found substantial losses in 4 floods on two major rivers in Australia. Figures in his report show losses of 12, 36, and 95 acre feet per mile on the Darling River, and

46 acre feet per mile on the Murrumbidgee River.

Keppel and Renard (ref. 54) reported on a study made in the 14-inch rainfall area of south-eastern Arizona, on a 58 sq. mile tributary of Walnut Gulch. In a very dry channel system, where runoff occurred only as a result of intense summer thunderstorms, transmission losses of 25 acre feet per mile were recorded. (See also ref. 55).

Sharp and Saxton (ref. 56) studied 57 selected flood events on 18 rivers in the Great Plains of the U.S.A. and reported that transmission losses averaged 40% of flood flows between upper and lower gauging stations which averaged 53 valley miles apart. Losses of over 200 acre feet per mile, approximately 75% of flood volumes, were found.

The exact nature of the loss in each case is not clear. Laurenson suggests that seepage into the river banks and evaporation can account for the losses that he encountered. Surface depressions in the flood plain could account for more during periods of overbank flow. In the western plains of New South Wales, groundwater levels are often substantially below the bottom of the river channel and leakage to groundwater from these effluent streams could also be a contributing factor. The influence of bank storage in abstracting from flood runoff and sustaining base flow between storms is discussed in the section on "Soil Moisture and Groundwater".

Sharp, Gibbs, and Owen (ref. 57) have prepared an empirical relationship which relates valley transmission loss to the ratio annual precipitation/average annual potential evapotranspiration. They reasoned that when precipitation is low and evapotrnaspiration high, vegetation on valley land draws heavily on soil moisture to considerable depths, and this creates a large storage capacity for water from the next flood. The relationship produced is empirical to suit the small amount of data available to these authors, and gives a multiplying factor to annual runoff.

(iii) Depression Storage in Farm Dams.

Where there are a large number of farm dams or larger storages in a catchment, the total yield of the area can be reduced by the increased evaporation and seepage losses afforded by the storages, in addition to the use of impounded waters for water supply or irrigation. The numbers of farm dams can be considerable in areas where they form the main source of stock water supplies. A number of surveys have been made to indicate the density of these dams in some states of Australia (refs. 58-61) and in the U.S.A. (ref. 62, 63).

There are, however, no research data available on the overall effects of these dams on water yields, and only one attempt has been made to estimate the likely effects. This is reported as part of a procedure for estimating the effects of land and watershed treatment on streamflow, developed in the Co-operative Water Yield Study in the U.S.A. (ref. 57).

The authors of this report estimated the water loss by ponds and reservoirs as a function of evaporation and seepage losses. Seepage was related to clay content of the soil, and allowance was made for the variable surface area of the reservoirs exposed to evaporation as water level fluctuated throughout the year. This procedure provides a single annual water loss from reservoirs but the reasoning used could be adapted to allow for this form of depression storage in a continuous simulation model of catchment behaviour.

(iv) Lakes and Swamps.

There is considerable variation in the type and scale of lakes, swamps, and depressions in Australia which can act as depression storage. On the grand scale, the entire Lake Eyre basin with an area of 500,000 sq. miles is a blind depression that does not drain to the sea. In the Murray-Darling basin, natural lakes such as Lake Victoria and the Menindee Lakes were once natural depression storages and are now developed to act as part of the storage system which regulates the river flow.

On the eastern and south-eastern coastal strip of the continent, many rivers pass through flat areas bordering the sea, and these contain depression storage for overbank flow from floods. The coastal area in the south-east of South Australia was permanently in swamp each winter until extensive drainage works were installed (ref. 64).

On a still smaller scale, and in a drier environment, there are areas of depression storage in the wheat belt of Western Australia, ranging from large lakes such as the Johnston Lakes near Norseman to small salt lakes of a few acres in area. There does not appear to have been any systematic study of swamps and lakes in Australia as depression storage in the hydrologic cycles. There is little information available to estimate the possible magnitude of such storage or its effects on the water yield of catchments, but it seems possible to incorporate this sort of storage into models of the runoff process if sufficient basic data is available.

One example of such modelling is given by Haan and Johnson (refs. 65-67) who describe a mathematical model which was developed to examine the effects of tile drain systems on flood flows from an area of swamps and depressions in Iowa and Minnesota. Large areas in this locality are characterised by numerous depressions and the area was very swampy in its natural state before subsurface drainage was installed. Popular opinion held that the drainage had increased flooding from the area by removing natural storage. Haan studied the geometrical characteristics of the depressions and found their storage capacity to be about $\frac{1}{2}$ inch of water. A mathematical model was developed to analyse the hydrology of the area with its drainage system. No effect on floods was found.

Woodward and Nagler (ref. 68) also report an investigation of the effects of agricultural drainage on floods in the Upper Mississippi Valley. Analysis of streamflow records from the Des Moines and Iowa Rivers showed no detectable influence on flood peaks by extensive drainage works.

8.4.3 Detention Storage

The main components of detention storage which might be influenced by the activities of man are:

i. the overland flow film

ii. channel storage in small channels

iii. channel storage in rivers

iv. detention in flood control dams

v. detention in swamps with slow but free outlet drainage.

(i) Overland Flow:

Most studies of overland flow have been engineering studies related to the stormwater drainage of airports and roads; consequently, more information is available related to flow over impervious surfaces than over natural surfaces. However, a lot of information of detention storage on natural surfaces has accumulated over the years.

The first experimental study of the mechanics of overland flow was by Izzard (ref. 69) and other investigations have been made by Woo and Brater (ref. 70) and by Yu and McNown (ref. 71). A review of these studies is given by Chow (ref. 72).

Where steady uniform overland flow is considered, the following relationship between rate of discharge and depth of overland flow can be theoretically derived:

$$Q = K.D^m$$

where Q = discharge

D = depth of flow

K is a coefficient involving slope and viscosity

m = 3.0 for laminar flow and about 1.67 for turbulent flow.

However, the realistic problem is one of spatially varied unsteady flow under rainfall in which the rate and depth of flow increase down the length of flow path. For these conditions, the relationship becomes:

$$D_e = K.L.q^{1/3}$$

where D_e = volume of detention when equilibrium flow condition is established.

L = length of flow

q = discharge per foot width at equilibrium

K is a coefficient depending on rainfall intensity, slope, and roughness of the surface.

Values of the roughness coefficients for surfaces ranging from smooth asphalt to dense grass turf are listed by Chow (ref. 72) and the hydrograph of flow over a variety of surfaces under conditions of steady rainfall can be calculated.

Another source of information of detention storages on natural surfaces comes from sprinkling infiltrometer experiments used to derive rates of infiltration. The method of analysing the runoff record from the infiltrometer to obtain the infiltration curve involves deriving a relationship between rate of discharge and mean depth of the detention storage in the infiltrometer. The method is described by Musgrave and Holtan (ref. 73) who show the relationships which have been recorded for a number of vegetated surfaces.

Studies on catchments are rare but Schiff (ref. 74) reports results from 9 small watersheds ranging in size from 0.65 to 2.71 acres. The period of study was from 1940 to 1949. There were 6 crop watersheds of size 0.65 to 1.69 acres, 3 of poor land use and 3 good land use; and 3 grassed watersheds, 2 in good condition and 1 in poor condition, ranging in size from 1.63 to 2.71 acres. Schiff reports the effects of cover density on the depth-discharge relationship of the overland flow film and on velocity of flow.

(ii) Channel Storage in Small Channels:

The discharge relationships of channels is normally calculated by an equation derived in 1889 by Manning (ref. 75). In English units, the form is:

$$V = \frac{1.49.R}{n}^{2/3} .S^{1/2}$$

where V = mean velocity of flow

R = hydraulic radius

S = slope of channel

n = roughness coefficient

The value of the roughness coefficient for grassed channels was first investigated by the U.S. Soil Conservation Service (Ree, ref. 76, Ree and Palmer, ref. 77, see also Chow, ref. 78). The Manning roughness coefficient for grassed channels is specifically known as the "retardance coefficient" and this is related to the product of mean velocity of flow V and the hydraulic radius R. Experimental curves for n versus V.R were developed for a number of American grasses ranging in height from $1\frac{1}{2}$ inches to 3 feet by Ree and Palmer.

In Australia, Eastgate (ref. 79, 80) has evaluated the relationships for a number of Australian grasses, and is currently (1969) setting up a calculation model of the combined overland flow-grassed channel flow path in order to analyse the effect of different spacings of contour banks on times of concentration and detention storages. Some recent work in Canada (ref. 81) has attempted to provide a quasi-theoretical basis for flow in vegetated channels.

Most soil conservation works directed to increasing detention storage are aimed at increasing the small-channel storage component by construction of contour or graded banks.

(iii) Channel Storage in Rivers:

Major floods on large catchments are caused by storms of long duration and large total volumes of runoff and rainfall. The influences of changes in overland flow and small channel detention storages are minimal under such conditions, and flood peaks are more influenced by channel storage in the major river and main tributaries.

The effects of human influence on flow in major channels has been studied more in relation to the empirical art of river improvement than to any calculation model for determining flood hydrographs. Strom (ref. 82) describes river improvement problems and practices in Victoria, and Reddoch (ref. 83) describes the same for the Hunter Valley in New South Wales.

On many rivers, the tendency to flooding is increased due to partial obstruction of the river channel by fallen trees, growing vegetation, or erosion debris. Clearing of the channel can increase the hydraulic capacity of the river and reduce overbank flow. Clearing and other river improvement works, such as the cutting of bends to steepen gradients and the construction of levees, all act to change the storage-discharge relationship of detention storage.

Strom (ref. 82) lists waterlogging, erosion and siltation in addition to flooding as the main problems related to river improvement in Victoria. Waterlogging can occur when the strip of land along each bank of the river is built up higher than the adjacent flats by silt deposition during overbank floods. These natural levees tend to block drainage from the flats back into the river and swamps develop between them and the high land bounding the river valley. The Orbost Flats in their natural state is cited as an example of this.

The report by Reddoch (ref. 83) shows bank erosion as the main reason for river improvement in New South Wales. Reddoch and Milston (ref. 84) point out that any improvement to the river channel which would have the effect of expediting the storm runoff from outlying sections of the catchment may increase the peak discharge at the downstream end of the improvements.

The effect on flood flows of any improvement to a section of river channel can be analysed by flood routing methods based on change in roughness coefficient or in slope or length of the channel. Maniak (ref. 85) describes a study in Germany in which a digital computer program was used to evaluate the effects of river improvements on 154 Km. of the Aller-Oker river system. An overall increase in peak flow of 20% resulted and this was compensated by the construction of detention storages.

(iv) Flood-Control Dams:

Soil conservation projects frequently include small dams either for flood-control (i.e. no permanent storage) or as storages, or as combined structures. Small dams for flood control are more common in the U.S.A. than in Australia, but many areas of Australia have substantial numbers of farm dams (refs. 58-61). The flood surcharge capacity of these dams have a small detention storage effect.

The mechanics of flood routing through these detention storages are well established, given data of inflow, storage, and spillway characteristics (e.g. see ref. 86). Analyses of the effect of a number of such storages on flood flows from a whole catchment have been made by Leopold and Maddocks (ref. 87), by Zingg (refs. 88-90), and by Hartman et al (ref. 91). These reports are described in more detail in the chapter on dams in Part I.

(v) Swamps:

The influence of swamps on reducing flood peaks can be calculated in the same way and from the same data as for flood routing through dams. Given details of any changes in storage capacity or in the outflow characteristics by human activities, it is possible to calculate the effect of the change on any inflow flood hydrograph. The problem of evaluating the influence on detention storage in swamps appears to be one of data collection only.

Costin (ref. 7) reports an experimental study which was made to evaluate the detention effects of a wetland community. Sphagnum bogs, Carex fens and associated wet heath communities comprise some 12% of the Guthega catchment in the Snowy Mountains. Measurements of detention effects and seepage losses from these communities were measured by applying artificial rain and then covering to prevent evapotranspiration losses while outflow was measured.

8.4.4 SUMMARY OF DEPRESSION AND DETENTION STORAGES

Depression and detention storages are particularly important in studies of the hydrological effects of change in land use. Many conservation and land treatment measures are purported to directly affect these components of the runoff process, both in reduction of total yield and in reduction of peak rates of runoff.

However, the concepts are poorly defined in the literature, and there is no established methodology for directly evaluating the capacities of the storages on a natural catchment. At best, the values can only be deduced indirectly by analysis of rainfall and runoff. This provides a poor basis for making any realistic assessment of how these storages affect the runoff process and how, in turn, the storages are affected by changes in land use.

8.5 INFILTRATION

The soil is the largest reservoir of water on most catchments, and the processes of water entry into and movement through the soil are of the upmost importance in the hydrological cycle. Infiltration is the entry of water into soil through the soil-atmosphere surface, and movement of water through the soil is referred to as percolation.

Bodman and Colman (ref. 93) have shown that, when water is freely available for infiltration at the surface, then the moisture distribution in the soil during infiltration is composed of a zone of saturation close to the surface, an unsaturated transmission zone of almost constant water content, and a wetting front.

In natural soils, the advance of a wetting front of infiltrating water is influenced by soil stratification and changes in porosity. When a low porosity horizon occurs in the soil below the surface layer, a saturated zone of positive pressure is established in the upper layer while infiltration proceeds under negative pressure and unsaturated conditions in the lower soil. Surface runoff begins when the upper soil layers are saturated.

The high rates of infiltration that occur while the upper layers are approaching saturation are usually treated as part of "initial loss", referred to in the previous section. The rate of advance through the unsaturated subsoil becomes the long-duration infiltration rate which approximates the storm "loss rates" which are used in flood flow estimation.

When water is applied to the soil surface, the rate of infiltration is initially very high, and then decreases exponentially to approach a low constant rate after a long period of time. Early thought as expressed by Horton (ref. 104, 105) was that the reduction in infiltration rate with time was more probably controlled by factors operating at the soil surface than by the flow process in the body of the soil. Swelling of soil colloids and the closing of soil cracks, sealing of the surface by fine particles, and compaction of the soil surface by raindrops were all offered as factors responsible for the decrease. Unfortunately, some of these concepts are still promoted today.

Modern infiltration theory has provided a more realistic basis for understanding infiltration behaviour in terms of the principles of continuity and flow governed by a potential. A review of developments in the theory and applications of the theory in practice is set out in a paper by Gardner (ref. 106), and another review is given by Philip (ref. 101).

Physics of the infiltration moisture profile have been set out in a series of papers by Philip (refs. 94-100). Just after water is applied to the surface of dry soil, the gradients in soil moisture suction are much greater than that due to gravity and results in a high initial absorption of water. Depth to the wetting front then increases as $t^{\frac{1}{2}}$(t = time) and infiltration decreases as $t^{-\frac{1}{2}}$ from the high initial rates. A higher initial moisture content in the soil initially decreases infiltration rate, although the wetting front moves faster through the soil.

After long periods of infiltration, the soil reaches a high constant water content approaching saturation for an appreciable depth below the surface. The infiltration rate into the soil then approaches that which is transmitted through the saturated soil by gravity only.

Philip found that the equation for total infiltration can be expressed as an infinite power series in $t^{\frac{1}{2}}$:-

$$I = S.t^{\frac{1}{2}} + A.t + B.t^{3/2} \ldots\ldots$$

where I is the total infiltration after time t and S, A, B, and the other coefficients are functions of both the soil-water diffusivity and the initial and surface water contents of the soil.

Philip termed "S" as the "sorptivity" because of its special significance, particularly during the early stages of infiltration. For horizontal inflow, all terms except the first become zero. For vertical inflow, the series converges rapidly and only the first few terms need be used.

While this theory provides a basis for predicting infiltration behaviour in a simple soil column, there are many complicating factors which influence the infiltration behaviour of a whole catchment. Soil properties are not constant, either in a vertical profile or over the area of a catchment. Surface soils are affected by incorporated organic matter, soil organisms, roots, and cultivation. Compaction by raindrops, animal hooves, and machinery can also have effects. Lull (ref. 112) presents a review of literature on soil compaction on forest and range lands; the extent of compaction by logging, grazing, and other agencies; and the effects of compaction on soil-water relations.

In 1937-38, the Committee of the American Geophysical Union on Physics of Soil Moisture surveyed research workers concerned with infiltration to review available information and current thought on the effects of organic matter on the rate of infiltration of water into soils (see ref. 107). The Committee circulated a questionnaire which included the following questions:-

(1) Effect of incorporated organic matter on the rate of entry of water into soils.

(2) Effect on rate of entry of water into soils due to the presence of organic matter on the soil surface.

(3) Effect of organic matter on the physical condition of the soil below it, in so far as it influences the rate of entry of water into soil.

(4) Effect of surface litter on filtering of silty water and thereby influencing the rate of entry of water into soil.

(5) Effect of the presence of organic matter in retarding runoff.

(6) Effect of organic matter on the water-holding capacity of soils.

(7) Change with time of the rate of entry of water into soil for measurements made while the rate was steady or unsteady.

The replies which are summarised in ref. 107 contained a considerable variety of information, ranging from results of laboratory studies involving artificial composted material incorporated into soil samples, to field plots and catchment studies. A very brief summary of the replies is as follows:-

to (1) most opinion held that organic matter increased rate of entry. Ploughing may give the impression of an increased rate when it may only be due to surface storage; it was found to be difficult to distinguish between these effects. Any influence of organic matter is so limited in heavy rain that effect on flood control is negligible.

to (2) most opinion held that organic matter on the surface increased the rate of entry but as in (1) it was difficult to distinguish from surface storage.

to (3) little information and conflict of opinion

to (4) little information and conflict of opinion

to (5) general agreement that organic matter retards runoff

to (6) there was agreement that organic matter increases water-holding capacity but the magnitude of the increase was negligible.

to (7) general agreement that rate of entry is highest at the beginning of application of water and decreased until approximately a steady rate was reached.

(A bibliography of 60 refs. to early and contemporary work is given in this report.)

There are additional factors which complicate infiltration behaviour in a natural catchment. Because of different drying rates in different parts of a catchment, antecedent moisture conditions can be very variable at the start of a storm and this can cause substantially different infiltration behaviour over a catchment.

Also, redistribution of water in the soil after rain finishes is complex due to hysteresis effects in the moisture holding characteristics of soil. Simulation of a series of wetting and drying cycles as in natural rainfall patterns involves overlapping a number of different infiltration patterns in which the drainage and redistribution of infiltrated water from one storm is incomplete before another storm commences. Watson (ref. 103) gives a description of the available theory for dealing with random patterns of wetting and redistribution. Hanks and Klute (ref. 108) describe a computer programme which has been prepared to simulate infiltration, redistribution, drainage, and evaporation processes. Hanks and Bowers (ref. 109) describe a similar programme for evaluating the equations for infiltration into layered soils, and Green, Hanks, and Larson (ref. 110) have shown that computer techniques can give a reasonable prediction of infiltration into a non-uniform field soil at several antecedent moisture conditions when sufficient description of the soil profile is available.

However, at the present time, there is little basis for directly applying infiltration theory such as that developed by Philip to the behaviour of whole catchments. The customary practice of "fitting" infiltration curves to rainfall and runoff records, either by hydrograph analysis as described by Musgrave and Holtan (ref. 73) or by optimising parameters in a catchment model as described by Boughton (ref. 181), produces a mathematical convenience rather than a description of a real phenomenon.

A great amount of information on the relative infiltration characteristics of different soil-plant complexes has been determined from infiltrometer experiments on small areas of a few square feet. Musgrave and Holtan (ref. 73) summarise much of the information available. However, it must be emphasized that there are marked differences in the rates of infiltration derived on small areas and storm loss rates derived from rainfall and runoff records on large catchments. There is no established method for using infiltrometer data to estimate the effects of change in land use on the behaviour of a whole catchment.

Sharp and Holtan (ref. 111) describe how the method of analysis for determining infiltration curves from sprinkled-plot experiments can be used to derive average infiltration curves for small catchments from rainfall and runoff records. Horton (ref. 104) put forward a method for determining the infiltration capacity of a large catchment. The capacity derived from Horton's method is what is now known as a "loss rate" i.e. an average rate of loss through the storm such that the amount of rainfall in excess of the loss rate equals the volume of runoff.

Loss rates are the indices of infiltration loss now widely used in flood flow estimation for engineering design purposes. They are most closely associated with real situations on large catchments; however, they are fairly insensitive indicators of any effects caused by change in land use because of the averaging of natural variability which is involved in their determination. Laurenson and Pilgrim (ref. 113) and Pilgrim (ref. 114) have reviewed available data on loss rate values and the factors which influence the rates.

The information on loss rates which is used in engineering design practice is in "Australian Rainfall and Runoff" (ref. 116) which has been prepared and published by the Institution of Engineers, Australia. The relative loss rate values for the different soil-plant complexes in this report should be regarded as guesses rather than an accurate summary of data. There seems to be little basis for using such information to estimate the hydrologic effects of change in land use.

One attempt which has been made to estimate values of infiltration parameters for a whole catchment without "fitting" has been made by Jones (ref. 115) in a study of parameter values for the Boughton catchment model. Jones attempted to relate infiltration values used with the model to properties of the catchment soils, but could not find any relationship. A surprising result of the study was that the infiltration values on the catchments studied were found to be highly correlated with mean catchment slope i.e. infiltration rates increased as catchment slope increased. It is doubtful that this is a general relationship but it illustrates the difficulty of assessing the effects of change in land use on infiltration behaviour.

8.6 SOIL MOISTURE AND GROUNDWATER

Water stored in the soil can be considered to be in two major components - one in the saturated zone of groundwater and the other in the unsaturated zone between the groundwater level and the surface of the ground.

Groundwater moves slowly through rock and soil and is the principle reservoir of water which sustains streamflow between storms. Water in the unsaturated zone is not held permanently against gravity and is also steadily depleted by drainage in addition to use by plants and other losses. Hewlett and Hibbert (ref. 117, 118) have shown that drainage of moisture from the unsaturated zone continues long after rain ceases and may be a primary source of sustained flow from small steep catchments.

Soil moisture is rarely if ever constant but certain soil moisture stages are useful in dealing with soil-water-plant relationships. Field capacity is the moisture content when soil is allowed to drain freely for about 48 hours from saturation. Permanent wilting point is the moisture content left in the soil when plants are unable to extract any more. The modern soil moisture suction equivalents of these are about 1/3 atmosphere and 15 atmospheres respectively. Marshall (ref. 119) gives an excellent review of these concepts.

The difference between wilting point and field capacity is the "available water" of the soil. Values of available water have generally been evaluated for irrigation purposes, and the draft Code of Practice for Sprinkler Irrigation Design (ref. 120) contains suitable data which have been collated for use with Australian soils.

The non-capillary storage between field capacity and saturation is about the same magnitude as available water storage and is more important in determining the movement of infiltrating water through the soil and the abstractions from storm rainfall. Jones (ref. 115) gives an excellent review of the data available for estimating non-capillary storage capacities.

Usually, available water and non-capillary storages are expressed in terms of inches of water per foot depth of soil. The total amount of water available for use by plants depends also on the root depth of the plant. Most data on root depths or "effective root depths" have been evaluated for irrigated crops - see ref. 120 for typical data. The total water available in the root zone, i.e. the product of available water and root depth, is usually termed the "root constant".

Jones (ref. 115) reviews publications by Boughton (ref. 180), Ozanne et al (ref. 121), the U.S.D.A. Soil Survey Manual (ref. 122), Shively and Weaver (ref. 123), Baver (ref. 124), Costin et al (ref. 125), Meinzer (ref. 126), Russell (ref. 127), and Donahue (ref. 128) to obtain suitable values of the root depths of grasses for use with the Boughton catchment model.

Penman (ref. 129) introduced the idea of variable root constant over a catchment area to allow for differences between grasses, trees, and riparian vegetation in a study of the water balance of the Stour catchment area in England. Kohler (ref. 130) describes water balance models used in the U.S.A. which incorporate different storage capacities for different parts of the catchment. The multi-capacity model of the U.S. Weather Bureau is probably the most well-known of these.

It should be noted that root constants used in water balance models are usually evaluated by "fitting" calculated runoff to observed runoff and not be actual measurements of root depths and soil moisture storage capacities on a catchment.

Pilgrim (ref. 131) reviews analogue and digital models of groundwater movement and gives a bibliography of 35 references to published work. Most studies have been related to development of aquifers for productive use rather than as a component of the hydrologic cycle.

Toth (refs. 132, 133) describes 3 types of flow system - local, intermediate, and regional - that may occur in a small basin and gives a theoretical basis for analysis of groundwater movement in small catchments. Hornberger et al (ref. 141) describe a model for study of water movement in a composite soil moisture - groundwater system. Knisel (ref. 134) analysed baseflow data from 61 drainage basins representing 9 geological formations in the southern-central U.S.A. to evaluate the relative groundwater storage capacities of the different geological formations. Van Voast and Novitski (ref. 140) give a detailed description of the subsurface water regime in the 665 sq. mile catchment of the Yellow Medicine River in Minnesota and how surface flow and water quality is related to groundwater movement. Other studies of the influence of geology on groundwater storage and streamflow have been made by Cross (ref. 135), Farvolden (ref. 136), Hely and Olmsted (ref. 137), and Schneider (refs. 138, 139).

Baseflow between storms can be sustained in a number of ways; by depletion of groundwater storage, by drainage of soil moisture from the unsaturated zone, and by depletion of detention storage in stream channels, lakes, etc. During storms, when river levels are high, water may flow from the river into bank storage. Brater (ref. 142) suggested that a quick stream rise could cause water to flow back into an aquifer creating a negative groundwater flow. Work by Todd (ref. 143), Rorabaugh (ref. 144), and Cooper and Rorabaugh (ref. 145) confirmed Brater's suggestion and showed that considerable time may be required for the resulting bank storage to drain. Kunkle (ref. 146) and Meyboom (ref. 147) show that a large part of base flow may be supplied by bank storage.

The most comprehensive review of baseflow, its analysis, and relations to geology and groundwater storage has been made by Hall (ref. 148) who gives a bibliography of 111 references including several prior reviews and annotated bibliographies.

The problems of salting following clearing, which has been described in the chapter on "Effects of Clearing", occur when shallow saline groundwaters come close enough to the surface in valleys and at the foot of slopes for evaporation of water and accumulation of salt to take place. The areas of accumulated salt sustain a high loss of productive capacity and value. In these cases, the movement of soil moisture and groundwater become items of major economic significance in the hydrologic cycle on the catchment.

Drainage is the most direct influence of human activity on groundwater and soil moisture storage. By removing water from the soil storage, the capacity for absorbing rainfall from storms is increased and, where the drained soil has an opportunity to dry, the rate of infiltration of water into the soil can be increased.

By lowering the groundwater level, drainage can reduce the amount of evapotranspiration loss of water. Saline groundwaters produce most trouble when salt accumulates as water evaporates. One of the principle uses of drainage in Australia is in lowering of saline water tables in irrigation areas where overwatering has resulted in high water levels rising close enough to the surface to produce salting problems (ref. 149).

8.7 EVAPOTRANSPIRATION

8.7.1 Introduction

There has been considerable study of the evapotranspiration process and it is impossible to review here all literature relevant to the evapotranspiration rate of different crops in different climatic conditions. Some general background is given to provide a basis for discussion of the effects of change in land use on the evapotranspiration component of the water balance and, where possible, reviews of past studies are cited without revising or quoting all of the reviewed material. Reviews by Veihmeyer (ref. 150) and McIlroy (refs. 169, 170) give a broad coverage of the subject and bibliographies of 158 and 63 references.

There are 4 broad aspects of evapotranspiration relevant to the study of how change in land use influences the water balance. These are:-

(i) the rate of potential evapotranspiration at a "point" or over a small area e.g. a lysimeter.

(ii) the rate of actual evapotranspiration loss at a point, and its relationship to the potential rate.

(iii) the variation in point rates over a natural catchment area,

(iv) variations due to type of cover and land management.

These aspects are considered in detail in the following sections.

8.7.2 Potential Evapotranspiration

The concept of "potential evapotranspiration" was introduced by Thornthwaite (refs. 151, 152). It is the hypothetical rate of water loss from a large homogeneous area of continuous green crop, under the given meteorological conditions, when there is no resistance to water supply at the evaporating surface. It was originally supposed to be independent of the nature of the crop and the soil, but evidence to the contrary now exists (Mather, ref. 153).

A brief review is made here of the different methods used for estimating or measuring potential evapotranspiration rate, and then the effects of different vegetated surfaces is discussed. For clarity, the methods are grouped into 3 categories:

(a) empirical correlations with climatic data

(b) water balance or inflow-outflow methods

(c) vapour-flow and energy balance methods.

(a) Empirical Correlations:

There have been many methods developed to correlate potential evapotranspiration rate with climatic variables such as temperature, pan evaporation, daylight hours, and cloud cover. The most commonly used methods have used either temperature data, e.g. Thornthwaite (ref. 152), Blaney and Criddle (ref. 154), and Lowry and Johnson (ref. 155); or pan evaporation e.g. Penman (ref. 156), and Hargreaves (ref. 157). Linacre (refs. 158, 159) gives a good review of these methods.

The reason for the many methods using temperature data is undoubtedly due to the abundance of temperature records, both in length of record and widespread coverage of recording stations. Pan evaporation records are rare by comparison, and most are of short duration; but the close relationship between potential evapotranspiration and evaporation from a free water surface makes this form of correlation both easy and attractive. However, the correlations are dangerous to extrapolate, particularly where the surroundings are such as to make the pan more or less of an oasis than the catchment it is meant to represent.

An improvement on the pan is the potential evaporimeter or p.e. meter (see refs. 153, 165). This consists of a sunken tank of soil containing vegetation typical of the surface under study, and surrounded by a guard-ring area of the same type and treatment. Frequent measured irrigations, plus regular collection and measurement of percolate from the base of the soil column, permit the p.e. meter's evaporation to be approximated very simply by input minus output.

Understanding of the physical processes of evaporation and evapotranspiration has progressed a great deal in recent years. Methods of estimating these components using vapour flow and energy balance techniques (discussed later) offer more accuracy and reliability than the empirical correlations. However, availability of data and ease of calculation will still be reasons for use of empirical methods for some time to come. It may be noted that almost all current mathematical catchment models use such methods for computation of the evapotranspiration loss.

(b) Water Balance:

Water balance methods of estimating evapotranspiration calculate the difference between input of precipitation and output of runoff, drainage, and any change in storage.

Et = precipitation - runoff - underground drainage - change in storage

The method may be applied to whole catchments or to small measuring volumes such as a lysimeter or pan evaporimeter. There are several variants of the basic method, e.g. underground drainage may be small enough to be ignored, or the period of study can be chosen such that change of storage within the system is negligible.

Lysimeters, particularly weighing lysimeters, have the advantages of accuracy and relative ease of measuring all components of the equation. A survey of lysimeters and a bibliography on their construction and performance was prepared in 1940 by Kohnke, Dreibelbis, and Davidson (ref. 160). This extensive review covers 250 years up to 1939 and includes a bibliography of 489 reports and papers. Another study by Harrold and Dreibelbis (ref. 161) reviews more recent studies up to 1955 and cites an additional 134 references. A symposium on lysimeters was held by I.A.S.H. in 1959 (ref. 162).

Lysimeters have been operating in Australia for several years (see McIlroy and Angus, ref. 163) with continuous recording balances accurate to 0.001 inch of water (McIlroy and Sumner, ref. 164). Slatyer and McIlroy (ref. 165) discuss the principles behind lysimetry and the performance of different types of instruments.

Inflow-outflow measurements of the water balance of whole catchment areas, for estimation of evapotranspiration losses, have been studied mainly in relation to irrigation water requirements. Papers by Blaney and others (ref. 154) and by Loeltz and McDonald (ref. 166) illustrate the method.

(c) Vapour Flow - Energy Balance Methods:

Over a century ago, John Dalton (ref. 167) laid the foundation for vapour flow methods of estimating evaporation in his bulk aerodynamic equation:

$$E = a(b + u)(e_o - e_a)$$

where E = rate of evaporation

a and b are empirical constants

u = wind speed

$e_o - e_a$ = vapour pressure difference between the surface and the bulk air

It is almost impossible to measure e_o directly, so in practice this approach can only be applied to saturated or very wet surfaces, for which e_o can be taken as the saturated vapour pressure at surface temperature, provided of course that the latter can itself be measured sufficiently accurately, So far the only major application has been to lake evaporation, for which the method is now established (Webb, ref. 198). The recent advent of infra-red thermometers suitable for field use may lead to its application to land surfaces

Direct measurement of water vapour flux has now been developed from a proposal by Swinbank (ref. 168), using hot wire anemometers with fine wet and dry bulb thermometers (see review by McIlroy, refs. 169, 170). The measurement of air-flow and vapour concentration which fluctuate rapidly, and their multiplication and integration over a period of time to obtain evaporation loss, require both minute rapid-response sensing elements and intricate electronic apparatus. Semi-automatic equipment of this kind (the Evapotron) has been developed and checked successfully against energy balance over pasture at Edithvale (Dyer, ref 171). A recent portable transistorised version has also perfomed well (Dyer and Maher, ref, 172).

The basic energy balance equation used for estimating evaporation and evapotranspiration is:

$$R = H + LE + G$$

where R = net radiative flux received by the surface

G = heat flux into the ground

H = sensible heat flux into the air

LE = latent heat flux into the air

Using the Bowen ratio H/LE, the ratio of sensible to latent heat fluxes into the air, the equation can be arranged for estimating evaporation or evapotranspiration as follows:

$$LE = \frac{R - G}{1 + B}$$

where B is the Bowen ratio.

McIlroy (ref. 170) describes the determination of the main energy balance formulae and also lists applications which have been made of the method to both free water and vegetated surfaces.

Combinations of the vapour flow and energy balance approaches have been made in 3 alternative procedures; independently by Penman (ref. 156) and Ferguson (ref. 173), and as a refinement of these methods by McIlroy (ref. 174). Penman and Ferguson were concerned most with free water evaporation while McIlroy's equation was directed to crop evapotranspiration. This latter method has been tested against the Aspendale lysimeters (McIlroy and Angus, ref. 175) and against those at Tempe and Davis in the U.S.A. (Pruitt and Lourence, ref. 176).

8.7.3 Actual Evapotranspiration

As moisture in the soil is reduced below field capacity, water available to growing plants is restricted and the actual rate of evapotranspiration loss can fall below the potential rate. If the evapotranspiration rate is measured by vapour flow instruments instead of estimated, then no trouble is encountered. It will be the actual rate recorded whatever the restriction on water supply. However, when potential rate is estimated using the relationships with climatic variables, then it is also necessary to estimate the ratio of actual to potential evapotranspiration rate as soil moisture is depleted.

Until 1962, there was considerable controversy about this relationship. The most well-known proposals were those of Veihmeyer and Hendrickson (ref. 177) who maintained that transpiration continued at the potential rate at all soil moisture levels from field capacity to the wilting point, and Thornthwaite and Mather (ref. 178) on the other hand, who proposed that transpiration decreased in a linear manner between potential rate at field capacity and zero at the wilting point.

It was shown by the work of Denmead and Shaw (ref. 179) that the ratio of actual to potential transpiration rate is not a single value depending only on the soil moisture level, but depends also on the prevailing potential rate. Their work has shown that transpiration can continue at the potential rate while the soil moisture is reduced almost to wilting point if the prevailing potential transpiration rate is low. When the prevailing rate is high, the actual transpiration rate is reduced below potential rate when the soil moisture level is only a small amount less than field capacity.

The experiments of Denmead and Shaw were on corn grown in containers with the soil surface sealed to prevent loss of moisture by evaporation. However, the same pattern of loss could be expected to apply to other vegetation types. Boughton (ref. 180) used a simplified version of the relationship in a catchment model for simulating the water balance of whole catchments and obtained satisfactory results. The same relationship has been adopted by Chapman (ref. 4) in the catchment model being developed by Division of Land Reserach, CSIRO.

8.7.4 Catchment Evapotranspiration Loss

The previous sections have dealt with the rate of evapotranspiration from a point or, more realistically, from a small area such as a lysimeter where conditions are relatively uniform. It is obvious that on a very large catchment such as the Murray-Darling catchment the rate of evapotranspiration can vary considerably - one location can be suffering extreme drought while another part of the catchment is snow covered.

Even on catchments as small as a few acres, variations in slope and aspect can cause large differences in the rate of evapotranspiration, and where shallow groundwaters are present, variation of only a few feet in the depth to the water table can produce substantial changes in the opportunity for surface evaporation or water use by plants.

Variations in slope and aspect cause big differences in the amount of radiant energy received and this can cause big differences in the evapotranspiration rate. The variation was described by Jacobs (ref. 182), by Jackson (ref. 183), and by Douglass (ref. 186). The most thorough analysis has been made by Lee (ref. 184) who reviews earlier work, provides a computational basis for calculating incoming energy, and gives a bibliography of 117 relevant reports.

The influence of slope and aspect on water use by plants is illustrated by clearing and thinning experiments which record the increase in water yield when catchment cover is converted from trees to grass. Hibbert (ref. 185) shows that the variation in water yield following thinning is strongly influenced by the aspect of the catchment as well as by the amount of clearing.

Undulations in the ground surface and aerodynamic roughness of the surface can affect the windspeed above it, as well as the degree of turbulent mixing for a given windspeed. The complex interacting effects of these factors, together with the effects of slope and aspect mentioned above, can be accounted for in theory using the extended combination method for the calculation of evapotranspiration loss (see McIlroy, ref. 170). However, the method involves use of different constants and parameters for different surfaces such as forest and grass, and at the present time, there is inadequate information of the numerical values of these items for making reliable estimates of the relative water use of different surfaces.

In addition, seepage of soil moisture and groundwater to the ground surface in drainage lines and at the foot of slopes can keep moisture available to vegetation in these areas while soil moisture in higher ground has been depleted. This can result in evapotranspiration loss continuing in some parts of a catchment long after the higher areas have dried out.

The two reasons given above can cause considerable variation in the rate of evapotranspiration over a catchment area. As yet no catchment model has incorporated any provision for this variation but slope and aspect are being allowed for in the model now being developed by C.S.I.R.O.'s Division of Land Research for analysis of data from catchments in the Australian representative basins programme (see Chapman, ref. 4).

8.7.5 Type of Vegetation and Management

Changes in the type of vegetation on a catchment and management activities such as thinning of a forest can cause variations in the evapotranspiration loss. The causes for which there is some evidence of effect on evapotranspiration are of 2 major types:

(a) differences related to availability of water

(b) differences related to availability of energy.

(a) Available Water:

The major hydrologic difference between trees and grass is the difference in soil depth from which the roots are able to extract moisture. Grasses are shallow rooting having an effective root depth, for purposes of water balance calculations, of about 1 to 3 feet. Trees, on the other hand, are relatively deep rooting with an effective root depth, depending on soil type, from a few feet to over 30 feet.

Where climatic conditions are such that evapotranspiration exceeds rainfall during the summer months, the soil profile is dried out over the root zone of the vegetation cover. This creates a moisture deficit which must be replenished in the following winter when rainfall again exceeds the evapotranspiration rate. Trees, which have an opportunity to extract more water than grass from a deeper root zone, can create a greater moisture deficiency during the summer and consequently produce a greater abstraction from rainfall in the early winter.

The result is that, in a winter wet-summer dry climate, there is less utilization of water by grass than by trees because of the reduced opportunity for water use, and there is more surface runoff or groundwater recharge under grass than under trees. Many of the experimental results reported in the chapter "Effects of Clearing" illustrate this difference.

Vegetation density can also affect evapotranspiration loss, particularly from forest stands. Douglass (ref. 186) gives a comparison of soil moisture distribution beneath thinned and unthinned stands of loblolly pine, and reviews studies of thinning by Bay and Boelter (ref. 187), Bethlahmy (ref. 188), Della-Bianca and Dils (ref. 189), Douglass (ref. 190), McClurkin (ref. 191), Moyle and Zahner (ref. 192), Tarrant (ref. 193), Zahner (ref 194), and Zahner and Whitmore (ref. 195).

Results from these studies show a clear tendency for a reduction in evapotranspiration loss related to a reduction in stand density. The reports on increases in streamflow following thinning, which are reviewed in the chapter on "Effects of Clearing", support this evidence.

However, it must be emphasised that there is little direct evidence in these studies of how much area of surrounding ground can be utilised by a tree in extracting moisture for transpiration. It appears that there could be a critical density for any species of given age, soil, etc., above which no increase in evapotranspiration loss would be expected but below which the utilization of soil moisture would be reduced. There is little evidence of what vegetation densities, particularly of trees, are required for maximum utilization of soil moisture.

(b) Available Energy:

Different vegetation types can produce changes in the energy available for evapotranspiration in two ways - by differences in reflection of incoming energy, and by differences in the amount of advective energy intercepted, such as between grass and trees.

Baumgartner (ref. 196) gives annual values for the absorption coefficient of shortwave radiation, indicating differences in the amounts of energy absorbed between forest, cultivated land, grassland, and bare soil, and he also gives differences in the amounts of total energy available for vaporization, expressed as mm of water evaporated.

Cover Type	Absorption Coefficient	Net Radiation
Forest	0.89	1000 mm
Cultivated Land	0.80	900 mm
Grassland	0.77	750 mm
Bare soil	0.65	595 mm

Penman (ref. 197) draws attention to the fact that most energy balance relationships for evaluating evapotranspiration loss were derived over grass or equivalent short crop, and there is no basis for a theoretical calculation for forests because of lack of suitable data. He suggests expected differences between grass and trees would be due to smaller reflection of incoming radiation by trees, and greater aerodynamic roughness of the trees.

There is little evidence to suggest any differences in the energy balance between different species of trees, in particular, between hardwoods and conifers. Douglass (ref. 186) reviews a number of studies between forests of different types, and concludes that "variations in rooting depth seem to cause the only significant difference in seasonal evapotranspiration from pine and hardwood stands."

8.8 Summary of Effects on Components of the Hydrological Cycle

The components of the hydrological cycle are often described in different ways, depending on the interests of the person concerned. While there is no widely accepted set of components, the descriptions generally follow similar lines and it is possible to delineate a number of parts of the cycle which might be affected by change in land use. For the purpose of this project the following have been adopted for study:-

- interception capacity
- soil moisture storage
- infiltration
- depression and detention storages
- evapotranspiration.

Each of these components has been considered from two points of view:-

(a) how does change in land use affect the component?
(b) how does change in the component affect water yield or flood flows?

Results of the study are summarised in the following sections.

(i) Interception:

Two substantial reviews of available data on measured interception capacities have been made in recent years, one in the U.S.A. and the other in Australia. Both show similar results i.e. that the values of interception capacity, measured by a number of different methods, are very low and in the order of 0.05 inches depth of water; and, second, that there are no systematic differences in interception capacity among trees, shrubs, and grass.

There is a little evidence to show that evaporation of intercepted water proceeds at a slightly higher rate than transpiration of water from dry leaves under similar conditions. The source of the additional energy required for the higher evaporation rate is believed to come from a cooling of the air, as evidenced by the temperatures of wetted leaves falling below those of dry transpiring leaves. It is not clear if this effect would extend over a large catchment.

There have been many studies of interception and many measurements of interception capacities. The terminology is complex involving a profusion of terms and concepts; however, there is no systematic evidence to suggest that different plant covers are much different in their interception capacities. Also, the only possible effect on runoff would appear to result from the slightly higher rate of evaporation from intercepted water than that which occurs from transpiring leaves under the same conditions. Even where frequent light showers separated by drying weather occurs, it seems doubtful that interception capacity is a major factor influencing either total water yield or flood flows from a catchment.

In alpine areas, there is a tendency for more snow to be collected in small clearings than under trees. This seems to be due to a redistribution of total snowfall rather than any actual increase over a large area; however, there may be opportunity to influence snow management if numerous small clearings were used to promote deep snowfall over these areas in place of a uniform fall over the whole catchment. Where moist fogs and fine mists occur frequently, trees collect more dew than grassed areas and may cause an actual increase in total precipitation.

(ii) Soil Moisture Storage:

One of the largest reservoirs of water in a catchment is the soil moisture, and the portion of this that lies in the root zone of the plant cover is of paramount importance.

Bare soil will lose only a small amount of soil moisture by evaporation before the rate of loss reduces to an insignificant amount, whereas plants are able to utilize soil moisture over the root zone and produce total losses up to about ten inches depth of water when climatic conditions permit. The soil moisture deficiencies created by plant transpiration are most important in determining antecedent moisture conditions which affect initial loss, infiltration rates, total abstraction from storm rainfall, and, as a result, both water yield and flood flows from a catchment.

The most obvious result that has been obtained from catchment experiments which involve change in land use is the increase in water yield or in groundwater recharge which occurs when trees on a catchment are replaced by grass. It seems clear that the difference is primarily attributable to the difference in root depths of the two types of plant cover, and the difference in the total moisture deficiency that can be produced. Where the climate is such as will allow sufficient drying between storms, trees can extract a greater total amount of soil water than grass, because of the greater root depth. The lesser soil moisture deficiency under grass results in less demand for replenishment from following storms and more surface runoff or groundwater recharge.

Many of the observations of differences in infiltration rates and in flood peaks between tree covered and grass covered catchments can be accounted for in terms of the difference in antecedent moisture conditions which result from the different moisture deficiencies produced by trees and grass.

(iii) Infiltration:

The profile of water infiltrating into a soil mass consists of a saturated zone in the surface layers of soil and an unsaturated zone between this and the wetting front. It is clear that entry of water through the surface of the ground is rarely the controlling influence on infiltration. The unsaturated zone below the saturated surface region is the factor controlling infiltration after the high initial rate is passed.

Cultivation and other practices which affect the surface have little influence on the body of the soil which controls the long-term infiltration rate. The major factor which affects this part of the infiltration pattern is antecedent moisture - the higher the initial soil moisture, the lower is the infiltration rate in the unsaturated zone. Therefore, the major types of land use which affect infiltration appear to be practices such as fallow which reduce evapotranspiration loss and keep soil moisture at high levels; and differences in total water use, such as between trees and grass, which result in different soil moisture deficiencies at the end of a dry period.

Some studies on bare soil suggest that surface sealing due to raindrop impact may be of importance in controlling infiltration, by reducing the rate of entry of water into the soil. It is emphasised that when the surface is bare of vegetation, there is no transpiration loss of water from the soil, and antecedent moisture levels will generally be higher than those in a soil covered by trees or grass, with subsequent lower rates of infiltration and less abstraction from following storms. The dominant role of antecedent moisture complicates the results of studies on surface sealing and similar factors, but little attention has been paid to this in the studies which have been made.

Modern infiltration theory provides a basis for understanding the process of infiltration into a soil column. The use of computers has enabled the development of methods for handling infiltration into layered soils of different properties, and for simulating the complex patterns of wetting and drying which occur in natural rainfalls. However, no studies to date have approached the complexities of a natural catchment where there is continuous variation in surface slope, soil depth, soil properties, evapotranspiration loss, drainage opportunity, and even the rainfall input.

Infiltration is usually considered in three separate ways - as infiltration into a soil column based on modern theory; as infiltration curves derived from infiltrometer experiments; and as loss rates on whole catchments derived from rainfall and runoff records. There are substantial and significant differences between the results of infiltrometer experiments and loss rates from whole catchments. The application of infiltration theory to the behaviour of whole catchments has not yet progressed to the point of explaining the difference or providing a basis for evaluating the effects of change in land use.

At the present time, it appears that two further developments will be needed before the effects of land use on infiltration on a whole catchment can be reliably assessed. The first development will be to allow for the effects of different plant types on antecedent soil moisture conditions, according to the different patterns of moisture extraction for transpiration use. The second will be to allow for the considerable variation which occurs over a catchment in such factors as the properties of the soil mass, rainfall, surface topography, evapotranspiration demand, and drainage opportunity.

(iv) <u>Depression and Detention Storages</u>

The major difficulties in the study of depression and detention storages is the lack of any definition as to what constitutes the storages, and the lack of any systematic method of measurement of either of them. On the small scale, some attempts have been made to measure "random roughness" of the ground surface, and to assess the increase in depression storage created by cultivation. On the large scale, a few particular examples have been studied, e.g. the effects of drainage of natural depressions on flood flows. However, no systematic study of these components of the hydrological cycle have been made.

Generally, it seems that depression storage does not have a major effect on the water yield of a catchment, contrary to what might be expected. Catchment studies of the hydrological effects of soil conservation programmes show that contour banks and terraces have no systematic effect on water yield, whereas practices such as fallow or reforestation that influence evapotranspiration loss have evident and consistent effects on yield. On small catchments in low run-off areas, a substantial amount of depression storage such as in farm dams must influence the water yield, but extensive investigations in both the U.S.A. and the U.S.S.R. have failed to show any significant effects on the yield of large catchments.

Many studies have shown that transmission loss in stream channels can result in substantial abstractions from streamflow. On small catchments, this is probably a significant factor affecting the water yield. However, on large catchments, the accretion to groundwater from this loss can reappear as base flow further downstream in some circumstances. The size of catchment is important in determining whether such factors are important or not.

Detention storages are most important in medium to large catchments. Flood detention dams are commonly used in the Small Watershed Program of the U.S. Soil Conservation Service to mitigate flood damages immediately downstream of the structures. On large catchments, detention effects of storage in the river channel are important in determining the hydrograph shape and flood peaks. Improving the channel efficiency by clearing and straightening can reduce flood peaks in the treated section, although the treatment may simultaneously result in increased flood peaks immediately downstream of the section.

There is sufficient knowledge of hydraulics available to determine the effects of detention storage on flood peaks on large catchments, using well-established routing techniques. There is not enough knowledge available to predict with accuracy the effect of depression storage on the water yield of small catchments.

(v) Evapotranspiration

There is a good deal of information available concerning the rate of evapotranspiration from a grassed surface when the soil moisture levels are high and water is freely available to the plants. Information comes from theoretical studies of the energy available for evaporating water, from input-output studies of the water balance of catchments, from lysimeter studies, and from a number of empirical correlations with meteorological parameters. However, there is much less information available concerning the evapotranspiration from a tree-covered area, and no data at present on which to base calculations of the likely difference in water use between trees and grass.

There are further complications on large heterogeneous areas such as natural catchments. Variations in slope and aspect can result in substantial differences in the incoming energy and produce different rates of evapotranspiration. Further to this, natural climatic patterns can produce repeated periods when soil moisture is depleted and is no longer freely available for use by plants at potential evapotranspiration rate. This reduction of the actual rate of water use below potential rate is very important in the water balance of catchments in regions where average annual evaporation is greater than two-thirds of average annual precipitation.

Because the root depth of grass is generally less than the root depth of trees, there is less total moisture available to the grass, and actual evapotranspiration rate of grass is reduced to less than potential rate much sooner than occurs with a tree-covered area. The difference can cause significant differences in the water balances of grass-covered and tree-covered catchments.

Two points have become clear in this review of information on evapotranspiration. First, the theoretical basis for calculating water loss from a variety of surfaces, when water is freely available, is in advance of the available data. There is a need for extension of field measurements to forested areas, including mixed communities of natural forest, in order to provide a basis for comparing different land uses such as grassed areas and forests.

Second, there is a need for more study of the reduction in actual evapotranspiration rate below potential rate as soil moisture levels fall below field capacity. There are differences in the opportunity for water use caused by difference in root depths of plants; and there may be other contributing factors such as the ability of some plants to conserve water when the supply is limited by closing their stomata. Some limited experimental results are available but, generally, the allowances made for these effects in current catchment water balance studies are still largely speculative.

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CHAPTER 9

MATHEMATICAL MODELS FOR EVALUATING EFFECTS OF CHANGE IN LAND USE

9.1 INTRODUCTION

Linsley (ref. 1) has presented an excellent review paper which traces developments in rainfall-runoff analysis over a period of 300 years, from the first measurements which showed that rainfall was sufficient to account for the volume of streamflow, to modern techniques of simulating the water balances of catchments in hourly time intervals.

Linsley draws attention to the change from simple empirical relationships between rainfall and runoff to the period of modern hydrology which began in the 1930's with the work of Horton and Sherman. To quote from Linsley:

> "Horton's paper on 'The Role of Infiltration in the Hydrologic Cycle' and Sherman's paper 'Streamflow from Rainfall by the Unit-Graph Method' represent together a milestone in hydrology. On the basis of these two important papers, hydrologists began to think in terms of a two-phase process. The problem of calculating the volume of runoff from rainfall was separated from the problem of defining the time distribution of the runoff at the gauging station. This separation of the two processes made it possible to look at the total system in a logical way and terminated the need for empirical relationships between rainfall and flood peak with drainage area being the primary parameter."

This separation is still relevant in analysis today. The problem of making an accurate assessment of the water balance to determine the amount of runoff which occurs, either as surface flow, interflow, or groundwater flow, is most commonly considered as a separate problem to the effects of detention storage and travel time that determine the outflow hydrograph shape from the pattern of excess rainfall. Developments in the two aspects are considered in the following sections.

Mathematical models of water quality most commonly require a runoff simulation model to determine flow as the basis for determining movement of pollutants. Water quality models are reviewed in the section following the runoff and groundwater models.

9.2 MODELS OF WATER YIELD

Linsley (ref. 1) has traced developments in estimating runoff from the paper on infiltration by Horton (ref. 2) in 1931, to the preparation of the computer simulation models at Stanford.

Following Horton's paper, a great deal of research and field measurement of infiltration was undertaken. One approach was the direct measurement of infiltration rates from infiltrometer experiments on small plots; another was to analyse rainfall and runoff data from flood-producing storms to calculate an average rate of infiltration during each storm. Results were found to vary widely and there were significant differences between results from the two methods.

The practical application that showed up the inadequacies of the infiltration approach was flood forecasting. This work is a prime example of the two phase nature of the runoff processes - first determining the amount of losses from storm rainfall, and then translating the pattern of excess rainfall into an outflow hydrograph which defines the peak flow rate. Hydrologists of the U.S. Weather Bureau found the unit hydrograph concept was an adequate technique for determining the hydrograph shape on areas of 1000 square miles or less. However, the infiltration approach proved to be quite unsuited to forecasting the amount of runoff.

Antecedent moisture conditions were found to be one of the major factors determining the amount of runoff from a storm and led to the development of "antecedent precipitation indices" (A.P.I.) (see ref. 4). This factor, combined with total storm rainfall, storm duration in hours, and a week-of-the-year parameter, in a graphical multiple regression relationship, provided the first reliable basis for operational flood forecasting.

In its simplest form, the A.P.I. model has a single store to represent the moisture holding capacity of a catchment. The moisture in store is depleted on a daily basis by multiplying with a constant (value usually about 0.85 to 0.98), then adding the daily rainfall for the day considered. When the daily rainfall is sufficient to exceed the current moisture deficiency, runoff is assumed to occur, either as a direct amount of excess or as determined by the multiple regression method. Table I illustrates a sample calculation using a catchment storage capacity of 4.0 inches, and a value of 0.9 for the multiplying factor.

TABLE I

Antecedent precipitation index model
Capacity = 4.00 inches; coefficient = 0.9;
starting from saturation, i.e. S = 4.00

Day	Rainfall (inches)	Soil Moisture Level (inches)	Runoff (inches)
1	-	3.60	-
2	-	3.24	-
3	-	2.92	-
4	0.05	2.63	-
5	-	2.41	-
6	0.50	2.67	-
7	2.00	4.00	0.40
8	1.00	4.00	0.60
9	0.10	3.70	-
10	-	3.33	-
11	-	3.00	-

With hand calculations prior to the advent of electronic computers, long term water balance calculations on a daily basis were possible but only with simple storage structures and very few calculations for each day. Digital computers were introduced into hydrology during the 1950's and by 1960, the speeds of the largest computers were already faster than manual or electro-mechanical calculating speeds by four to five orders of magnitude. This introduced not only faster ways of performing older methods of analysis but also completely new methods of attack.

The most significant new method was the digital simulation of the hydrological cycle by Crawford and Linsley (refs. 7-11) by means of the Stanford Watershed Model. This model is a moisture accounting procedure, using hourly rainfall and daily evapotranspirations as input, and computing hourly streamflows as output. When a catchment receives snow, the model contains a subroutine which keeps an account of snow on the ground and calculates the rate of melt (Anderson and Crawford, ref. 10). The water melted from the snow is fed into the model and treated as precipitation.

All water entering the catchment is accounted for until it evaporates, infiltrates to groundwater or enters a channel as runoff. The computer programme routes the runoff from where it enters tributary channels to the outlet for which the hydrograph is being determined.

In its initial form, the model required very complex information describing the characteristics of the catchment in order to operate. Numerical values were needed for 32 constants and three arrays, these being 28 constants describing physical characteristics of the catchment, four constants to specify initial moisture conditions, and arrays to describe infiltration characteristics, interflow characteristics, and channel routing. Reports by Anderson and Crawford (ref. 10) and James (refs. 12, 13) have tabulated values for specific catchments, but trial-and-error adjustment to fit observed runoff is still necessary.

In later versions of the model, the operational data were simplified but the model is still complex and difficult to use. The writer knows of three independent attempts to use the Stanford model in Australia which finally lapsed because of this operational difficulty. It would be fair to report that the Stanford model has been used very little away from its point of development, even though it has been the inspiration for much other work. The operational difficulty probably accounts a great deal for this.

Following the Stanford watershed model, there have been a number of other models developed in the U.S.A. The best-developed and most-reported of these is that by the U.S. Geological Survey (see refs. 14-17). The model is impressive for its application to flood frequency studies in contrast to the applications to yield estimate of most other models; however, the most impressive aspect is the study of parameter sensitivity (see refs. 15, 16).

An important innovation has been incorporated into a model by Huggins and Monke (refs. 18-20) at Purdue University. They sub-divide a catchment into a number of small elements by a square grid network. The maximum number of elements is apparently unlimited, but each element must be small enough to represent a single component with uniform slope, aspect, vegetation, etc. Six processes are simulated for each element - interception, infiltration, interflow, depression storage, surface detention, and surface runoff. To date the model has been tested on two small (two acre) areas with reasonable success.

In Australia, a comprehensive review of methods available for estimating catchment yield was made by Ayers (ref. 21) in 1962. A more recent review of methods suitable for small rural catchments was made in 1968 by Laurenson and Jones (ref. 22) and this includes a review of runoff process models.

Two models developed in Australia have proved to be fairly successful. The Commonwealth Bureau of Meteorology developed an initial loss - loss rate - unitgraph model for flood forecasting. An antecedent precipitation index is calculated daily and this has been related to initial loss (see ref. 23). When the initial loss is satisfied, runoff is assumed to begin. A single value of loss rate is subtracted from following rainfall in six-hour time periods and the rainfall excess is then translated into flood peaks and river heights at downstream locations.

The other model, which was designed to simulate catchment water balance to estimate daily volumes of surface runoff, is that by Boughton (refs. 25-27). This model was the first detailed simulation of the water balance of catchments to be made on a digital computer in Australia. Basically, the model is composed of a number of moisture stores with operating rules to govern the movement of water into, out of, and between the stores. Daily rainfalls and monthly evaporation data are used to estimate daily volumes of runoff.

Since development, Boughton's model has been tested under a wide variety of conditions. It was amended to include a groundwater flow component and used to generate a synthetic flow record on the Darwin River for design of a dam to supplement the Darwin water supply (ref. 28). It has been adopted by the Hunter Valley Research Foundation for study of the water resources in the Kingdom Ponds - Dartbrook catchments of the Upper Hunter Valley (ref. 29). At the present time, the Australian Water Resources Council is testing the model on a large number of Australian catchments as part of a research project on both yield and flood flow estimation on small rural catchments. The model developed for the Council for analysis of data from the Australian representative basin network (see Chapman, ref. 30) has the same basic structure as the Boughton model with the operating rules developed to use time periods less than one day during storm periods.

Jones (ref. 31) has made a detailed examination of how the values of parameters in the Boughton model might be determined from field measurements. He simplified the model structure, derived interrelationships between some of the variables, and tested his conclusions on four catchments.

In New Zealand, the model has been successfully applied to five small catchments (ref. 27) and is now being developed further at the University of Otago for study of the Upper Taieri catchment (Hutchinson, pers. comm. 1969). In the United Kingdom, Murray (ref. 32) has used the model in a study of the Brenig catchment, and the Devon River Authority has used the model to provide information on runoff for a Select Parliamentary Committee (Herbert, pers. comm. 1968).

Two other models, one developed in Australia and the other tested here, should be mentioned. Bell (ref. 33) developed a runoff model and tested it with data from a 60-acre catchment in the Lidsdale State Forest. To date, the model has not been applied to any other catchment.

An American procedure which has been more widely tested in Australia (but with less success) is the runoff curves method developed by the U.S. Soil Conservation Service (ref. 35). The application of this method for estimating runoff from ungauged catchments in Australia has been discussed a great deal in the literature, but the one major test which has been made gave disappointing results.

This test was carried out by the Snowy Mountains Hydro-Electric Authority which analysed 18 station years of runoff data from six farm dams and one research catchment in Queensland (ref. 34). It was found that the method consistently underestimated the occurrence of runoff, correctly predicting only 57 occasions out of 179, and in estimating runoff magnitude, the error in nearly half of the derived runoffs was about 80% or greater. This method is currently being tested on a wider range of catchments as part of the Australian Water Resources Council research project on yield and flood flows from small rural catchments.

9.3 MODELS OF THE RUNOFF HYDROGRAPH

Many developments in hydrograph analysis arose from the unit hydrograph concept introduced by Sherman (ref. 3). The unit hydrograph concept has been the subject of many papers - too many to list in detail here - but some of the major steps in development can be cited.

Snyder (ref. 36) was the first to relate parameters of the unit hydrograph to physical characteristics of the catchment. Gray (refs. 37, 38) also developed relationships of this type. Others have expressed the unit hydrograph shape in terms of catchment shape and slopes, e.g. Clark (ref. 39) proposed the concept of the unit hydrograph as a routed time - area diagram of the catchment.

In 1958, Nash (ref. 40) presented his concept of the unit hydrograph as the end product of a series of successive linear storages in the catchment. His work was followed by Dooge (ref. 41) in 1959, who used linear storages interspersed with time delays. Laurenson (ref. 42) reviews these models in a study of runoff routing methods of hydrograph synthesis.

The unit hydrograph concept is based on a premise of a linear input-output relation. This basis has been the subject to a considerable amount of theoretical analysis. The paper by Amorocho (ref. 43) is typical of the attempts to introduce non-linear methods into the analysis of hydrologic systems.

The basic flow equations of continuity and momentum provide a basis for exact analysis of the flow in channels, and recent work such as that described by Machmeier and Larson (ref. 44) has been directed towards use of these equations for routing unsteady flow through the channels network of a catchment. The model developed by these authors can be used to examine the effects of slope, roughness, and cross-section of the channel on hydrograph shape. However, studies of the effects of change in land use on hydrograph shape are very few.

Linsley (ref. 1) makes the point that, if the water balance part of a catchment model is effective and produces an accurate time distribution of runoff increments, then a relatively simple storage routing procedure is sufficient to reproduce the hydrograph with considerable accuracy. On the other hand, if the storage and retention on the surface and the infiltration losses are not correctly modelled, then it is impossible to reproduce the hydrograph. Linsley says:

> "It is probable that the nonlinearity indicated by many analyses of stream hydrographs is as much a result of incorrect assessment of the runoff increments and improper treatment of the division between surface runoff and interflow as any other possible causes."

The International Hydrology Symposium held September 6-8, 1967 at the Colorado State University, Fort Collins, includes many reports of hydrograph models in the 82 papers presented. Proceedings of the symposium have been published by the university. The diversity of current approaches to hydrograph synthesis is well illustrated in these papers. The current approaches are not reviewed in detail here as progress in this field has not developed to the stage where the effects of changes in depression and detention storages caused by changes in land use can be realistically modelled with any accuracy. The reader is referred to the proceedings of this symposium for an up-to-date coverage of hydrograph models.

9.4 GROUNDWATER MODELS

Because of the complex boundary conditions which generally occur in nature, analytical solutions to the behaviour of groundwater systems are rarely feasible. Prior to 1950, analogues were frequently used to model groundwater systems and these are still common today. The I.A.S.H. symposium on Use of Analogue and Digital Computers in Hydrology (ref. 45) in 1968 describes a number of analogue models. Detailed reviews of analogue methods and models have been made by Karplus (ref. 46), Bouwer (ref. 47) and Lawson and Turner (ref. 51).

With the advent of digital computers, it became possible to use digital simulation models with numerical methods of analysis instead of analogues. Pilgrim (ref. 48) has reviewed the use of digital models for regional groundwater studies, as distinct from the hydraulics of single bores or wells, and his paper includes a bibliography of 35 reports. Pilgrim reports that digital models can simulate complex field situations with good accuracy, even though models of regional groundwater have undergone only a few years of serious development. Digital models already appear to have some advantages over electric analogues and the advantages seem certain to increase in the future.

Geiger and Hitchon (ref. 49) have given a detailed review of the requirements of a groundwater study in a research catchment, and their paper includes a bibliography of 66 relevant reports. Toth (ref. 50) has made a detailed theoretical analysis of groundwater flow problems in small basins.

9.5 MODELS OF WATER QUALITY

Concurrent with developments in mathematical models of streamflow, there has been considerable development in recent years in the modelling of water quality in rivers and estuaries. Models vary according to the different types of pollution being analysed, e.g. Reid et al (ref. 53) developed models for four classes of pollution, characterised as:

i. biodegradable (organic oxygen demanding substances);

ii. nutritional (plant nutrients, particularly nitrogen and phosphorous);

iii. persistent chemicals (salts, pesticides);

iv. thermal.

Their models were used to estimate treatments and dilution requirements for pollution loads in 22 river basins in the U.S.A. for the years 1980, 2000 and 2020.

Thomann, O'Connor and DiToro (ref. 55) have reviewed the state of the art of constructing mathematical models of water quality. Thomann (ref. 56) originally investigated the problem in the Delaware Estuary in the U.S.A. and developed a general mathematical approach to the problem of describing time and space variations of dissolved oxygen in a river. Using this model, Thomann and Marks (ref. 57) formulated a linear programming model to determine what combinations of waste treatments should be made to secure the required water quality standards at minimum overall cost. Graves, Hatfield, and Whinston (ref. 58) extended this model of the Estuary to include by-pass piping of water. A number of other papers have described the modelling of this project (see refs. 67-73).

Models of dispersion in natural streams are concerned with determining how concentrations of a waste change with distance downstream from the source. Models of the longitudinal dispersion process date from the work of Taylor (ref. 61) and Aris (ref. 62), but the dispersion coefficients found in natural streams are much larger than predicted by their analyses. Fischer (refs. 63, 64) has shown that some of the variation in the dispersion can be explained by the effect of transverse velocity gradients.

Schnelle, Thackston, and Krenkel (ref. 65) describe an improved model of dispersion in turbulent streams from work by Hays (ref. 66) which divides the stream into a main zone and a stagnant or dead zone. Thackston and Krenkel (ref. 59) have reviewed available information and methods for evaluating longitudinal mixing coefficients. These authors, together with Hays (ref. 60) have proposed a least squares procedure for estimating the coefficients.

O'Connor (ref. 74) has presented a comprehensive discussion of the factors that influence the dissolved oxygen of streams. Loucks and Lynn (ref. 75) have developed mathematical models for predicting the probability distributions of minimum dissolved oxygen downstream from a waste source, based on assumptions of streamflow and waste concentration and magnitude. Thayer and Krutchkoff (ref. 76) have developed a stochastic model that produces a probability distribution for both BOD and DO at points downstream from a waste source.

Some of the largest models have been developed for the problem of managing salt in whole river valleys where irrigation development has created major concentrations of saline waste water. A review of the principles and problems of salt balance in river systems is given by Pillsbury and Blaney (ref. 78). Orlob and Woods (ref. 80) describe a very detailed model for the Sacramento River in California which was based on an earlier study for the Lost River (ref. 79).

The Sacramento river system is comprised of 21 separate irrigation units. Modelling included water storage in surface streams, soil moisture, and groundwater. Orlob and Woods list the important requirements of a water quality model as:

i. compatability with a dynamic hydrologic model of the same system;

ii. facility for accommodating time-dependent decay functions;

iii. facility for time-delay of quality constituents brought about by interaction with the physical media through which the constituent must pass.

It was envisaged that their model will ultimately possess the capability for describing the fate of both conservative and non-conservative pollutants, particularly pesticide residues, within complex hydrologic environments.

Giglio et al (ref. 54) give a qualitative description of the use of systems analysis for regional planning of waste management. Loucks (ref. 77) also discusses the advantages and limitations of a systems approach for planning rational water pollution control policies. The main objective of a systems approach is usually to minimise overall cost. The two main types of economic models which have been applied to water quality systems are dynamic programming and linear programming.

Shih and De Filippi (ref. 81) have formulated a dynamic programming model to minimise the total costs to water users and waste producers in a river system. The model handles both conservative wastes, which are not changed appreciably in a river except by dilution, and non-conservative wastes which are degradable biologically. Liebman and Lynn (ref. 82) have developed a dynamic programming model for minimising the cost of providing waste treatment to meet specified dissolved oxygen standards in a stream. They apply the model to a simple example based on data from the Willamette River in Oregon.

Revelle, Loucks and Lynn (ref. 84) prepared a linear programming model for the same Willamette River example, and compared the results with the dynamic programming solution. The two techniques yielded essentially the same result.

The linear programming model of the Delaware Estuary has been previously mentioned (refs. 68-71). An alternative approach was tried by Dornhelm and Woolhiser (ref. 73) who developed partial differential equations to describe the unsteady, one-dimensional mixing process in an idealised, homogeneous, linearly-expanding estuary. An attempt was made to verify the results using data from the Delaware estuary but the results obtained were poor.

Generally, as much if not more success has been attained in the development of water quality models compared with runoff models. In Australia, not much use has been made of water quality models until very recently. Currently (1969), the Local Government Department of Queensland is investigating the use of mathematical models for analysing data from water quality surveys which are being made in some 50 rivers extending from the southern border to north of Cairns (ref. 83). In South Australia, modelling of salt movement in the lower Murray River is being undertaken. Use and application of water quality simulation models is still much less than of runoff models.

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CHAPTER 10

CATCHMENT MANAGEMENT LEGISLATION

10.1 INTRODUCTION

Control over a water supply prior to its distribution for use may be exercised in 3 ways - control over the use of land in the catchment providing the supply; foreshores protection or control over the land immediately adjacent to the river bank or edge of stored water; and control over access to and use (usually recreational use) of the stored water in dams.

The control over land use in catchments for protection of a water supply is the aspect most relevant to this project. The control may be exercised for a number of reasons. The principal objective is usually to control water quality and prevent pollution. The second purpose is most commonly to mitigate soil erosion and sediment production. Problems of stormwater drainage can be difficult in suburban areas and there is a good deal of legislation related to this aspect. Very little administrative concern is given to aspects of land use which may affect the quantity of water yield of a catchment.

The catchments in which land use is of most significance and concern are those providing town and city water supplies. Many activities which would pass unnoticed in the catchment of a dam providing irrigation supplies or water for power generation are strictly excluded from catchments used for metropolitan water supplies. Generally the principal concern in catchments for irrigation or power generation is that of erosion control. In catchments for town and city water supplies, pollution control is paramount.

Rural land use involves many activities which affect the quality of runoff water to a significant degree. Pig farming is regarded as a high risk activity in water supply catchments because of the danger of parasitic infections. Dairying and poultry farming are also troublesome because of the high concentrations of animal wastes.

In recent years, leaching of nutrients from agricultural lands has become a problem of practical importance. Fertilizers washed from farms in the Brisbane River catchment have caused prolific growths of the diatom Synedra at the pumping site for Brisbane's water supply. These organisms produce an unpleasant taste in the water and also rapidly block the water filters. In Western Australia, serious algal and sponge growth in the main conduits from Mundaring weir to the goldfields have been attributed in part to the use of fertilizers on farming properties abutting the watercourse above the weir. Algal blooms have also caused problems in the Millbrook Reservoir on the Torrens River near Adelaide and also in storages in Victoria and in New South Wales.

Many water supply authorities have been given statutory control over the farming activities which may be carried out in the catchments with which they are concerned. However, mining leases have on occasion been granted in water supply catchments against the wishes of the supply authority. In Western Australia, there are bauxite mining leases in the catchments providing water supply to Perth. In addition to any deleterious effect these may have on the water quality, some leases have encompassed experimental catchments previously established for research purposes.

The Tomago sand beds which provide part of Newcastle's water supply contain rutile to the value of some tens of millions of dollars, and a number of mining leases have been granted over fringe areas of the water supply areas. In the catchment of the Warragamba reservoir providing water to Sydney, open cut limestone quarrying has recently been permitted at Colong. There are coal mines on the foreshores of this storage and silver mining at Yerranderie. Grant (ref. 26) describes some of the provisions of the N.S.W. Mining Act, 1906, under which these activities are carried out.

In the time available for this project, it has not been possible to trace and review all legislation relevant to the effects of rural land use on water supplies. The situation varies from state to state and often there is overlapping legislation, particularly in connection with pollution of water. However, the information which became available during the project has been set out in the following sections of this chapter on a state-by-state basis, to illustrate the types of legislation relevant to catchment management and the variety of controls which exist. A short review of legislation in the U.S.A. and in New Zealand is also provided to give some perspective to the Australian information. Horsfall (ref. 32) gives a description of the city water supply practices in 13 British and European cities with details of the administration of the reservoirs and the catchments.

Two other studies should be noted. During 1969, a Select Senate Committee of the Federal Parliament was conducting hearings relevant to water pollution in Australia.

A prime concern of the Committee was the esisting legislation relevant to pollution control. The Committee is expected to present its report to the Senate during 1970 and this will be a comprehensive and authoritative statement of the problems and existing legislation throughout Australia. In addition, a review of water law in Australia is being prepared for the Australian Water Resources Council, by Mr. Clark, Senior Lecturer in the Law School of Melbourne University.

10.2 QUEENSLAND

Water supplies for Brisbane are drawn from the Brisbane River at the Mt. Crosby weir, about 18 miles by road from the city. The catchment area at this point is about 4,000 square miles. Two upstream storages help regulate the flow to the pumping storage. Somerset Dam, located about 80 miles from Brisbane, is built across the Stanley River 4 miles above the confluence of the Stanley and Brisbane rivers. The catchment above this dam is 515 square miles. Lake Manchester Dam is located on Cabbage Tree Creek about 12 miles above the Mt. Crosby pumping station and this has a catchment of 28.5 square miles.

The water supply is administered by the Brisbane City Council which has only small control over land use in the 4000 square miles of catchment. The small catchment above Lake Manchester Dam is half owned by the Council and half is State forest. Access to this area is restricted. The Council also owns the catchment of the Brisbane River immediately adjacent to the pumping pond of the Mt. Crosby weir extending for 6 miles along either bank of the river. This area is leased for farming but farm operations are controlled, e.g. pig farming is not permitted.

The remainder of the Brisbane River catchment is either State forest or used for agriculture and grazing. Dairying is carried out along the river flats and fruit and vegetable crops are grown. There are several towns in the catchment and these contain a few butter factories and one abattoir. The Council has estimated that the cost of acquiring the catchment as a water supply reserve would exceed $200 millions. The total capital investment in the water supply works is in the order of $30 millions. Consequently, little control is exercised over land use in the catchment and the water supply is fully treated before distribution.

Under the provisions of Section 120 of "The Metropolitan Water Supply and Sewerage Acts, 1909 to 1962", the Council has power to take action against the pollution of the Brisbane River and its tributaries above Mt. Crosby weir. In practice, the powers are punitive rather than preventative. With an almost completely occupied catchment, it is possible to prevent only gross pollution entering the river from readily detectable sources such as the effluent from a factory, but it is impossible to prevent pollution from the whole catchment. Farming practices which increase the turbidity of the water, and leached nutrients from agricultural lands which cause 'blooms' of organisms in the Mt. Crosby pumping pond, have been identified as major sources of pollution.

The Co-ordinator General of Public Works is responsible for co-ordination of all water pollution control activities in Queensland. Technical aspects of pollution control are delegated to the Department of Local Government which is carrying out catchment surveys in some 50 rivers to identify rural sources of pollution as well as those from factories, sewerage treatment works, and urban areas. In 1969, one water supply catchment had been partly surveyed, surveys of two more were being planned, and investigations had been made in four others. Local government authorities in Queensland have power to control water pollution under the Health Acts, the Canals Act, and the Sewerage, Water Supply and Gasfitting Acts.

The Soil Conservation Act of 1951 includes provision for the declaration of areas of erosion hazard in cases where three-fifths or more of the occupiers of land within an area petition for this action, or where the Minister is of the opinion that this action is necessary for the mitigation of erosion. The River Improvement Trust Act deals with works which are implemented for the purpose of mitigation of damage to streams by flooding and erosion. When a Trust is proclaimed for a stream it assumes control of construction activities relating to the stream, and also has powers for the regulation of undesirable practices on the catchment area.

10.3 NEW SOUTH WALES

The authorities principally concerned with catchments providing town and city water supplies in New South Wales are the Metropolitan Water, Sewerage and Drainage Board in Sydney, the Hunter District Water Board concerned with Newcastle's water supply, and the Department of Public Works.

The Metropolitan Water, Sewerage and Drainage Board owns very little of the catchment areas providing Sydney's water supply although it has some control over land use in the areas. The major catchment is the area of 3,480 square miles supplying Warragamba Dam. This consists of large areas of forests and agricultural holdings with concentrations of population at scattered points, including the inland cities of Goulburn and Katoomba.

Most of the catchments of the Cataract, Cordeaux, Avon, Nepean, Woronora, and Bargo reservoirs are Crown lands; the Board owns some lands, and the remainder are alienated. The smaller catchments of Fountaindale Creek, Jerrara Creek, and Hyam's Creek consist mainly of farming lands.

The Board administers its catchments, other than the minor schemes and the much larger Warragamba catchment, as single purpose water supply areas. Activities which could cause contamination, soil erosion, or disturbance of plant cover are strictly controlled by the Board under its statutory powers.

The Metropolitan Water, Sewerage, and Drainage Act No. 50, 1924-1963, provides for the proclamation of any land as a catchment area. Under Section 55 of this Act, sale of crown land within a catchment, other than within a city, town or village, is not permitted. The sale of crown land within a village, etc. is only permissible with approval of the Metropolitan Water, Sewerage and Drainage Board.

The Act provides that if a Public Authority proposes to grant a licence under the Forestry Act, a lease or licence under the Mining Act, permission or franchise under the Local Government Act, a licence under the Public Health Act, Dairy Supervision Act, Cattle Slaughtering and Diseased Animals and Meat Act, or Noxious Trades Act, a licence under the Water Act or to construct a railway under the Government Railways Act affecting any land within a catchment area, notice is to be given to the Board and any dispute may be referred to the Minister for settlement.

By-law 13 - Catchment Areas -- of the Act provides for:-

Prevention of pollution generally.

Notification of certain diseases and control of burials.

Control of pigsties, cowyards, etc.

Control of trade wastes, pit and mine waters and refuse.

Control of - destruction of pests
- disposal of dead animals
- slaughtering of beasts

Control of construction of private dams

Control of timber cutting

Control of straying stock

Prevention of bush fires

Control of removal of soil, rock, etc.

Control of picnicing, camping, disposal of nightsoil, etc.

Control of sewage treatment works, septic tanks, etc.

The Cataract, Cordeaux, Avon, Nepean, Woronora, and Picton catchment areas are proclaimed under Section 55 of this Act. Other catchments controlled by the Board are proclaimed under the Country Towns Water and Sewerage Act, and under the Local Government Act.

The Local Government Act of New South Wales (1919) provides that The Governor may, on the recommendation of the Minister for Public Works, proclaim catchment districts and ordinances may be made applicable to the districts. These are generally aimed at the prevention of pollution by prohibition of bathing, noxious trades, burial of diseased or dead animals, nightsoil or garbage. The relevant local government authority controlling the storage is responsible for policing the ordinances. The Department of Public Works is responsible for the catchment of the Fish River Dam.

The Soil Conservation Act, 1938-52, authorised the constitution of the Soil Conservation Service of New South Wales and created the Catchment Areas Protection Board. Some four years earlier, an ad hoc committee of departmental officers known as the 'Erosion Committee' had been constituted to make a general survey of the extent of erosion in the State. A Catchment Areas Board also had been constituted under an amendment to the Crown Lands Act in 1935 to deal with applications related to the settlement of crown lands and to impose any necessary conditions for the mitigation or prevention of erosion.

The Catchment Areas Protection Board constituted by the 1938 Act is authorised to determine whether Crown Lands in catchment areas shall be dealt with under any form of lease or licence and, if so, the conditions to be applied. The Board can also made recommendations to the Government for regulation of land use on other than Crown Lands, e.g. on the recommendation of the Board, the N.S.W. Government prohibited grazing and firing on the country above 4,500 feet in the high catchment areas of the Snowy, Murray, and Murrumbidgee Rivers.

The Soil Conservation Act of 1938 constituted the catchment area of the Snowy River and its tributaries as an area of erosion hazard, and provision was made in the Act for other areas to be notified as such. The catchment areas of Burrinjuck and Wyangala Dams and the N.S.W. portion of the catchment area of the Hume Dam were constituted under the Act and about 20 others have since been notified.

This Act provides a number of provisions which gives the Soil Conservation Service power to require landholders in notified catchment areas or areas of erosion hazard to undertake soil conservation work. For the most part, these provisions have not been enforced, mainly because the staff of the Service is fully occupied in meeting voluntary requests for assistance.

The Hunter Valley Conservation Trust Act of 1950 gives the Trust control over land use which might cause serious erosion in the Valley, and the Trust is empowered to compel landholders to undertake soil conservation works, to limit grazing and cultivation, to preserve timber, to destroy rabbits, etc., where serious erosion threatens. River improvement works in the Valley are authorised under the Hunter Valley Flood Mitigation Act of 1956 which gives responsibility for works above tidal influence to the Water Conservation and Irrigation Commission and works in the tidal zone to the Public Works Department.

The Water Act of 1912 as amended, which is administered by the Water Conservation and Irrigation Commission of New South Wales, is exercised mainly to regulate the utilization of water in rural areas. However, the powers of the Act also encompass pollution of water from agricultural, mining, and other sources. Section 21.A of the Act makes it an offence to discharge wastes from animal yards, cess pits, etc., or to leave dead animal carcasses in the bed or waters of a river, lake, etc. The powers are generally exercised when a complaint is received by the Commission, and no general preventive control is exercised.

There are about 10 Government departments or instrumentalities in New South Wales exercising some authority related to water pollution. At the time of writing (1969), there is a Bill before the New South Wales Parliament to provide for the control of water pollution and to establish a Water Pollution Advisory Committee.

10.4 AUSTRALIAN CAPITAL TERRITORY

When the site of the National Capital was selected, the boundaries of the Territory were designed to include water supply catchments, notably the Cotter River catchment and the

Naas-Gudgenby catchments, and the Commonwealth also reserved prior rights over the Molongolo-Queanbeyan River system which rises and flows for its main part in New South Wales before entering the Australian Capital Territory. To date only the Cotter River catchment has been developed for water supply purposes and it is also the only catchment reserved solely for the purpose of producing water (although some 10% of the area is under pine forest). The other catchments are used mainly for sheep farming and grazing with small populations of about 500 persons each.

Control of the catchments is vested in the Minister of the Interior and various ordinances related to soil conservation, fire control, etc. are administered by the Department of the Interior. An inter-departmental committee, The Cotter Catchment Committee, is set up to co-ordinate policy on controlling the catchment and its development, but it has no executive power other than to advise the Minister. It was on the recommendation of this Committee that pine planting in the catchment ceased in 1961.

10.5 VICTORIA

Water supplies for the city of Melbourne are drawn from uninhabited, single-purpose catchments which are vested in the Melbourne and Metropolitan Board of Works. When the Board was constituted in 1891, existing reserves for water supply were vested in it and, in the years following when additional catchments were required, the Government gave similar control over the new areas to the Board. A policy of strict exclusion of all habitation and utilization from the catchments has been pursued.

Pressure to utilize the valuable timber resources on the catchments resulted in an enquiry by the State Development Committee in 1959-1960. The final report of this Committee on 'The Utilization of Timber Resources in the Watersheds of the State' recommended that controlled logging on the catchments be permitted but the Government made no change to the past policy of single-purpose utilization.

Need for additional catchment areas arose soon after this enquiry and a report on 'The Melbourne Metropolitan Future Water Supply' was made by the Parliamentary Public Works Committee in 1967. Additional catchment areas were again given to the Melbourne and Metropolitan Board of Works, but in this instance, the areas have been vested for a limited period of ten years. Current research work by the Board and the Land Utilization Committee of Victoria will be influential in the Government's action at the end of the ten year period.

Generally, water in streams in Victoria is Crown property and its control for all purposes including town water supplies is under the administration of the State Rivers and Water Supply Commission. The Commission exercises its authority either directly by itself supplying water to towns such as those in the Mornington Peninsula and in the Castlemaine-Bendigo area, or through the agency of local Waterworks Trusts or Water Authorities constituted under the Water Act by the Governor in Council. In the Geelong district and the Latrobe Valley, separate authorities, viz, the Geelong Waterworks and Sewerage Trust and the Latrobe Valley Water and Sewerage Board respectively, have been constituted by acts of Parliament, and are responsible for the usage of water resources in those areas with co-ordination and development being under the general control of the State Rivers and Water Supply Commission. By 1960, 164 Waterworks Trusts and local governing bodies had been constituted in the State.

Water supply catchment areas for the country towns are usually not under the complete control of the water authority involved. A few examples of the major towns will illustrate. Ballarat is supplied with water from a total catchment area of 24,200 acres, of which 6,850 acres (28%) is vested in the Ballarat Water Commissioners. The Colac Waterworks Trust draws water from the Olangolah and West Gellibrand Rivers which have adjacent catchments of 2,500 and 3,500 acres respectively. The Olangolah catchment is Crown land under the control of a Committee of Management comprising representatives of the Lands Department, Colac Waterworks Trust, and the State Rivers and Water Supply Commission. Some 2,750 acres of the West Gellibrand catchment is owned by the Trust and the remaining area of 750 acres, which was formerly alienated and cleared, has now reverted to the Crown and been declared a water supply reserve.

The Latrobe Valley Water and Sewerage Board owns a buffer strip one-half mile in width around its Moondarra reservoir on the Tyers River. The remainder of the 105 square miles of catchment area supplying the Latrobe Valley is State forest under the control of the Forests Commission. The town of Erica with a population of 300 is within the catchment. The Final Report of the State Development Committee on the utilization of timber resources in the watersheds of the State gives a description of 25 catchments and the water supply authority concerned with each.

The major control of rural land use in water supply catchments in Victoria is exercised by the Soil Conservation Authority. The soil Conservation and Land Utilization Act passed in 1950 established the Authority and also provided for the establishment of the Land Utilization Advisory Council. The Council was given the function of advising the Minister concerning the proclamation of water supply catchments in Victoria. The Authority, in consultation with the Council, determines:-

(a) the most suitable use in the public interest of all lands in catchment areas;

(b) which of such lands should be permanently used for forest purposes and which may, without deterioration of or detrimental effect to water supply, be used for pasture, agriculture or any other purpose;

(c) the conditions under which various forms of land use may be permitted.

The Chairman of the Soil Conservation Authority is Chairman of the Land Utilization Advisory Council and other members are the heads of Government departments responsible for agriculture, forestry, lands, water supply, mines, and fisheries and wildlife. Since 1950, thirty-four water supply catchments have been proclaimed and land-use determinations made concerning allowable use of land in part or all of eighteen catchments.

Victorian legislation concerned with pesticides and stream pollution by pesticide residues is reviewed in the 'Report of the Committee of Enquiry appointed by the Honourable the Premier of Victoria to Enquire into the Effects of Pesticides'. Provisions of the Health Act and Poisons Act, administered by the Department of Health, concern the use of pesticides and agricultural poisons and the pollution of water supplies by residues. The recommendations of the Committee included the following:

> 'The Fisheries Act and Stream Pollution Regulations under the Health Act should be extended to prevent .... any pesticides from entering a stream, except in approved circumstances and conditions'.

10.6 SOUTH AUSTRALIA

Adelaide is supplied with water from a number of reservoirs as well as by pumping from the River Murray. The reservoirs are located on the South Para River with a catchment area of 88 square miles, on the Torrens River with a catchment area of 134 square miles, the Onkaparinga River with a catchment of 172 square miles, and the Myponga River with a catchment of 48 square miles. All of these catchments are inhabited and used agriculturally for apple and pear production, sheep and cattle grazing, dairying, market gardening, as well as pig and poultry raising. Public roads traverse the catchment areas and small townships are located within them. There are reserves around each reservoir from which the public is excluded.

The Engineering and Water Supply Department of South Australia administers the water supply undertaking. A permanent committee called 'The Advisory Committee on Water Supply Examinations' is charged with the responsibility to examine and make recommendations concerning measures to prevent pollution of the catchments. This committee is comprised of departmental heads in the fields of water conservation, bacteriology, geology, forestry, and engineering. All the catchment areas are regularly policed by an Inspector of Watersheds under the direct control of the Chief Chemist at the Bolivar laboratories. His duties are to detect and prevent pollution of the catchments and to ensure that any wastes discharging into streams are to prescribed standards.

10.7 WESTERN AUSTRALIA

The Metropolitan Water Supply, Sewerage and Drainage Board of Western Australia has approximately 1000 square miles of catchment area vested in it by the State Parliament for water supply purposes. Alienated lands within the area have been purchased as funds became available and owners were willing to sell, and there is little alienated land on the catchment now in use.

The Department of Public Works of Western Australia controls 2 major reservoirs which supply water to inland areas. Mundaring Weir with a catchment of 569 square miles supplies water to the inland mining towns of Kalgoorlie, Boulder, etc. and to the agricultural towns and farmlands east of Perth. Wellington Dam with a catchment area of 1,115 square miles supplies water to the southern districts around Collie.

Control of the catchment areas of these reservoirs is exercised through the Country Areas Water Supply Act. This Act provides control over land development, road construction, and agricultural and horticultural activities. The Department also pursues a policy of buying up alienated lands in the catchments when opportunity permits.

10.8 UNITED STATES LEGISLATION

Statutory controls over water supply catchments in Australia vary from the complete control such as that exercised over the areas providing water for Melbourne, to the almost complete lack of control over the areas providing Brisbane's water supply. Overseas practice tends more to the Brisbane example with water supplies drawn from alienated lands and full treatment given to the water before use.

Water law in the U.S.A. is complex and it is difficult to make any reasonable summary of the catchment management legislation which is exercised. There are many more water authorities in the U.S.A. than in the same area of land in Australia. A major study currently being made of the integrated water supply and demand situation in the whole Northeastern U.S., authorised by Public Law 89-298 of the Congress, illustrates the position.

The area concerned includes all New England states, all of New Jersey, Delaware, the District of Columbia, and parts of New York, Virginia, and West Virginia. In this area of 200,000 square miles with a population of 50 millions, there are 3680 water utilities including 50 water systems serving populations of 50,000 or more in the New York metropolitan area alone (see Kennedy, ref. 1). Caulfield (ref. 2) has estimated that some 40,000 town and city governments and possibly as many as 5000 private companies provide water supply and sewerage undertakings in the U.S.A.

Another feature of the U.S.A. is the multiplicity of laws, both State and Federal, related to water. An excellent outline of these laws is given by Trelease (ref. 7). The Legislative Reference Section of the U.S. Congress made a study of how water resources were involved in work of the 89th Congress, in session from Jan. 1965 to Oct. 1966. It was found that 1289 legislative measures, more than 5% of the total number of bills and resolutions introduced, were water related. The results are described by Schad (ref. 3, 29) and by Krausz and Meyer (ref. 4).

In general, most town and city water supplies are drawn from alienated lands which are used for timber production, agriculture, and recreational use. Pollution problems appear to be of most concern in the statutory control over use of the catchments. Hamilton and Nierop (ref. 8) report:

> 'In most states, the Departments of Health have statutory powers to control and supervise the production and distribution of water for domestic purposes. Under this authority, many community water supplies are covered by specific rules and regulations concerning the sanitation of surface waters and watershed lands from which such supplies are drawn. In general, the regulations prohibit any activities conducive to impairment of water quality and prescribe methods to be employed for removal or correction of pollution sources'.

The only direct control of catchment lands by water authorities appears to be where the lands are owned by the authority concerned. Even then, public pressure and government direction have resulted, in general, in multi-purpose use of the lands, with recreational use rather than agricultural use being of principal concern. Examples of the permitted use of catchment areas and the controls applied are given in a number of symposia in the U.S. literature (see refs. 11, 12, 13, 14).

Multi-purpose use of catchment lands is so well established that the principal controversy currently concerning recreation is whether recreational use of the reservoirs themselves should be permitted - a concept not much accepted yet in Australia. Wurtz, Dolcan and Bridges (ref. 5) and Baumann (refs. 6, 30) report the results of nation-wide mail questionnaire surveys of the recreational use of reservoirs in the U.S.A.

This aspect of catchment management legislation overlaps the general field of pollution control legislation, and the scope of this field is too wide to review here. The work by Gindler (ref. 9) is a basic text on U.S. Federal and State laws and regulations. The bibliography by Jacobstein and Mersky (ref. 10) is also an excellent source of information.

The second major aspect of catchment management legislation in the U.S. is related to flood control, and is mainly Federal legislation related to funding and participation of Federal agencies. The Flood Control Act of 1936 originally divided Federal participation between the Army Corps of Engineers, who were responsible for major dams on the main streams of river basins, and the Soil Conservation Service of the Department of Agriculture, who were responsible for land treatment and catchment management measures designed to mitigate floods and sediment production.

One feature of this Act was that the initiative for catchment protection works rested with the Federal authorities. This changed in 1954 with the passing of Public Law 566, otherwise known as The Watershed Protection and Flood Prevention Act. This Act deals with catchments not exceeding 250,000 acres (approx. 400 square miles) and provides for Federal funding of works, but requires local initiative in sponsoring projects. The Act is described by Steele and Sandals (ref. 16) and in reference 17.

This Act has resulted in a large amount of consequent State legislation to enable local authorities to sponsor projects. Otte (ref. 18) gives a review of the State district laws and statutes which have been enacted for this purpose, and Heath (ref. 19) presents a model enabling Act which sets out details of proposed regulations for controlling watershed lands among other items. Amendments to and developments of Public Law 566 since its enactment are described by Lowry (ref. 20) and the relation of court-established laws to the Act are reviewed by Ellis (ref. 21).

10.9 NEW ZEALAND

New Zealand is of special interest to Australia by reason of the close proximity of the two countries and the common heritage which is shared. However, climatic and topographic differences have produced little similarity in the hydrological problems of catchment management. The relevant New Zealand legislation is of interest for the contrast it provides to Australia rather than as a similar example.

Initially, New Zealand has no division into states and the complexities of Federal-State relationships are avoided. Secondly, the high mountains and high rainfall have made flooding, soil erosion and drainage the principal problems of legislative concern. More recently, pollution is becoming an increasing problem.

McGill (ref. 22) lists the statutes which deal with water in New Zealand, and Collins (ref. 23) traces the development of statute law related to catchment management from the middle of the last century to the present. The Public Works Act of 1876, the Rivers Board Act of 1884, and the Land Drainage Act of 1893 were important in establishing statutory control and public authorities to deal with river control and land drainage problems. But the present situation results from three Acts - The Soil Conservation and Rivers Control Act of 1941, The Waters Pollution Act of 1953, and The Water and Soil Conservation Act of 1967.

The Soil Conservation and Rivers Control Act established a central authority, the Soil Conservation and Rivers Control Council and local authorities, the Catchment Boards. It made provision for dealing with soil erosion, and brought soil conservation and river control work together in the new authorities. Generally, each catchment board is staffed with soil conservators who deal with works for mitigating erosion in the upper parts of catchments, and engineers who deal with river control works in the lower reaches of the main rivers to mitigate flood damages. The division has similarities to the Department of Agriculture -- Corps of Engineers division of flood control responsibility in the U.S.A. The establishment of these catchment boards was well in front of U.S. progress in the introduction of local authority in planning and undertaking catchment management works.

The Waters Pollution Act of 1953 established the Pollution Advisory Council whose function it is to promote the prevention or reduction of pollution of water by research, education, the formulation of codes and model by-laws about the treatment of trade wastes, and by determination of standards of quality for the water in any stream. The Council has eleven members who are representatives of local and central government and industry.

The Water and Soil Conservation Act of 1967 set up the National Water Authority and a Water Allocation Council. These, together with the Soil Conservation and Rivers Control Council and the Pollution Advisory Council form the present National Water Organization. The catchment boards have been constituted as Regional Water Boards under the new Act.

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CHAPTER 11

ECONOMIC EVALUATION OF CATCHMENT MANAGEMENT PROJECTS

11.1 INTRODUCTION

As late as 1955, there were relatively few publications related to the economic evaluation, specifically benefit-cost evaluation, of water resources projects. In the last 15 years there has been a profusion of reports, papers, text books, and other material presented, and there is considerable current interest and activity in the economic aspects of water resources. Most of the interest and published material are concerned with the evaluation of developmental projects, e.g. the construction of dams, development of irrigation areas, and similar works. It would be fair to state that catchment management aspects are considered least of all and have received least attention of any part of water resources evaluation.

Two activities have been responsible for most of the little published information available on evaluation of catchment management projects. In the U.S.A., economic evaluation has been required for works in the Small Watershed Program of the Soil Conservation Service in order to attract Federal funds, and this has resulted in a good deal of information related particularly to flood mitigation works. The general field of soil conservation has also been studied for many years and there are a number of publications related to the economic evaluation of soil conservation works and practices. Relatively few publications are available on other aspects of catchment management.

Economic evaluation studies are important in this review even though there is very little published information in Australia. Economic studies usually show those effects and results of catchment management which can be numerically assessed, and often serve to clarify fact from fiction. For example, the evaluation studies of the U.S. Small Watershed Program show that flood detention dams and channel improvements are the works which justify Federal funds for flood mitigation in the U.S.A., not the cultivation, conservation or land treatment measures which are often emotionally promulgated as having an effect on reducing flood peaks. In addition, the economic factor often serves to indicate the relative social importance of different works, and this can be of use in assessing research priorities where knowledge is inadequate.

There is little opportunity in this project for a detailed review of economic evaluation procedures related to water resources in general. However, there is merit in drawing attention to the sparse information which is particularly related to catchment management. The objective of this project is to draw attention to the gaps in current knowledge concerning catchment management, and that relevant economic evaluation knowledge lags noticeably behind the state-of-the-art of evaluation of water resources development projects.

In the following sections, a brief general background of benefit-cost evaluation in the U.S.A. is given, and then the information available concerned with flood control, water yield, and water quality aspects of catchment management is reviewed. The later sections contain descriptions of studies dealing specifically with soil conservation and forestry aspects.

11.2 BACKGROUND

The technique of benefit - cost analysis had its beginnings in the United States in the water resources programme of the Army Corps of Engineers. Hammond (ref. 5) has reviewed its history and identified 1902 as the year when the procedure was introduced for guidance in cost sharing between local and Federal interests. The procedures used were simple and restricted to direct and tangible costs and benefits.

The Flood Control Act of 1936 gave an impetus to development of economic evaluation methods when the Congress directed that benefits of projects "to whomsoever they may accrue" shall be included, and this opened up new concepts in the secondary, indirect and intangible categories. The Act also started the Department of Agriculture on investigations into the use of land treatment measures and upper catchment works for flood control, and works of improvement in 11 catchment areas were authorised in 1944. When Public Law 566, the Watershed Protection and Flood Prevention Act, was passed in 1954, the Department was authorised to initiate some 60 watershed projects.

Throughout the period 1936 to 1956, the main emphasis of catchment management works was on flood control. An important amendment, Public Law 1018 which was passed in 1956, and another amendment in 1958 authorised a wider range of purposes for these projects. Multi-purpose projects incorporating water for irrigation, drainage, municipal and industrial purposes, recreation and other uses then became possible.

In 1961, Ford, Greenshields, Riggs and Tolley (ref. 10) prepared a summary of the benefits which had been included in 160 projects up to May 1, 1958, and reported that these were in the following order of importance in the projects:

1. Flood prevention
2. Drainage
3. Irrigation
4. Recreation and wildlife
5. Municipal and industrial water.

The Federal Inter-Agency River Basin Committee appointed a Sub-committee on Benefits and Costs in 1946 to formulate principles and procedures for determining benefits and costs for water projects and the recommendations of this Sub-committee were reported in what has become known as the "Green Book" (ref. 3). The Bureau of the Budget set out directions rather than recommendations for evaluation of benefits and costs in its Circular A-47 (ref. 12) as described by Musgrave (ref. 11) who traces developments in appraisal procedures up to the issue of Senate Document 97 (ref. 4).

In Australia, benefit-cost evaluation of water resources projects is relatively new and to date very little attention has been given to catchment management aspects. There is little Australian literature which can be reviewed apart from some qualitative essays on forestry protection of water supply catchments (e.g. refs. 88, 89). The overseas literature is far more extensive and more useful as a guide to the information currently available.

Three symposia have been held dealing with aspects of this subject. A symposium on Economics of Watershed Planning was held at Knoxville, Tennessee in 1959 (ref. 2) and this included 20 papers which deal with many aspects of the small watershed programme of the U.S. Soil Conservation Service. A seminar on Project Evaluation in Agriculture and Related Fields was held in New Zealand in November, 1967 (ref. 6) and 15 papers were presented. A symposium on the management of municipal water supply catchments was held at the University of Massachusetts in November, 1965 (ref. 16) and included several papers dealing with economic evaluation of catchment management programmes.

Any review of economic evaluation procedures is of necessity complicated by the fact that the procedures used and the conclusions reached in the papers and books included in the review will depend to a large extent on the objectives of the firm, organisation, state or national government setting the evaluation objectives. In addition, economic efficiency is not necessarily the only evaluation criterion that may be used. For instance the United States Water Resources Council has published a report of a special task force set up by it entitled "Procedures for Evaluation of Water and Related Land Resource Projects" (ref. 109), which lists the following categories of national objectives as a basis for developing appropriate evaluation procedures:

1. National income objective
2. Regional development objectives
3. Environmental objectives
4. "Well-being" objectives.

The national income objective is the economic efficiency objective. The increase in national income attributable to a project or plan is the measure of its contribution to this objective. The regional development objectives embrace several related components such as increased regional income, increased regional employment, improved regional economic base, improved income distribution within the region, and improved quality of services within the region. The environmental objectives include the conservation, preservation, creation, or restoration of natural, scenic, and cultural resources in order to enhance or maintain the quality of the environment. The "well-being" objectives include such objectives as security of life and health, national defence, personal income distribution, and inter-regional employment and population distribution.

However, there is another body of opinion which considers that the economic efficiency criterion alone should be used in project evaluation when considering national investment and that the other objectives should be dealt with by political and administrative processes - see for example Eckstein (ref. 110). The Australian Treasury's "Investment Analysis" (ref. 7), has been written from this point of view. For further discussion on reference 109 from different points of view, see references 111 and 112.

11.3 FLOOD MITIGATION AND DRAINAGE

In the field of economic evaluation of effects of land use, there is more information available related to flood control than any other aspect. The reasons are twofold. First, the Flood Control Act of 1936 and the Watershed Protection and Flood Prevention Act of 1954 in the U.S.A. emphasised flood control as a primary objective in attracting Federal funds to projects. Second, reduction in flood damages is relatively easy to delineate and evaluate compared with other benefits of watershed programmes.

Smith (ref. 17) describes the three components of a typical scheme in the U.S. Small Watershed Programme as (a) land treatment, (b) gully stabilizing structures, and (c) flood retarding dams. It is clear from this paper and that by Buie (ref. 18) that the primary reduction in flood damages is effected by the floodwater retarding dams, or improved stream channels to reduce overbank flow, or a combination of both. The land treatment measures have greatest effect in reducing erosion and sediment damages.

The floodwater retarding structures are usually earth dams which are larger than the farm dam which is common in Australia. Francis (ref. 19) gives a description, based on averages of 2500 dams in small watershed projects which illustrates the type of structure involved. Earth fill averages 80,000 cubic yards with costs (in 1963) averaging $50,000; flood pool capacities average 900 acre feet.

It is pertinent to draw attention to the flood control controversy which occurred in the United States in the 1940's and early 1950's. The Flood Control Act of 1936 divided responsibility for flood control between the Department of Agriculture and the Army Corps of Engineers. Initially, the Department of Agriculture works were land treatment measures with relatively few proposals for the construction of flood detention dams. The Corps of Engineers was concerned with major downstream dams.

For a decade following the passing of the legislation, there was little conflict between the authorities. Shortly after World War II, policy of the Department of Agriculture changed and proposals for flood-detention dams of medium size appeared in their reports. These proposals were for dams in the order of 50 feet high covering 200 acres or so at spillway level and designed to control flooding in the tributary streams of the river basins.

The Corps of Engineers became highly critical of these structures and this was the basis of the "flood control controversy". In turn, conservationists put forward much criticism of the large Army dams (e.g. see Big Dam Foolishness, ref. 20; and ref. 107). The controversy is reviewed in admirable detail by Leopold and Maddocks (ref. 21). These latter authors made a study of the reduction in flooding which could be expected from a number of medium sized dams on tributaries versus one large dam on the main stream of a river channel.

Studies by Zingg (refs. 22-24) show that land treatment measures and small headwater dams can reduce peaks of small floods in small catchment areas but the effect on floods is reduced as the amount of storm runoff is increased. Zingg evaluated the costs and flood control benefits of farm ponds averaging 2.3 acre feet capacity and concluded that ponds kept empty as flood retarding structures could recover only 40% of their cost in saving flood damages while ponds allowed to fill for other reasons would save only 8%.

Buie (ref. 18) describes the U.S. Soil Conservation Service method of evaluating a watershed project. An historical flood series, usually about 20 years duration, is selected as the basis for evaluation (or alternatively, analysis of the frequency distribution of floods may be made). Current damageable values within the flood plain are determined. The selected storm series is flood routed through the watershed and flood damages under the present conditions are determined by damage schedules taken from farmers in the damage area. The reduction in runoff resulting from the application of land treatment measures for land protection is first calculated. The storm series is again flood routed using the reduced runoff figures. The resulting damage reduction is credited to the land treatment measures, and the remaining damages become the base for evaluating the flood prevention works. The effect of the proposed system of structures is determined by an additional flood routing.

Cohee (ref. 25) gives an example of evaluating benefits and costs from three types of works - contouring, terracing and flood retarding structures. The first two of these increase land productivity. The latter reduces flood damages to crops and pastures, fences, roads and bridges (both public and on-farm), damage to urban properties, and from deposition of infertile sediments and bank erosion.

Cormack and Timmons (ref. 26) give an example of evaluating the increased productivity and reduced erosion and floodwater damages on the 3,140 acre Hound Dog Creek catchment in Iowa. Pavelis and Timmons (ref. 27) describe benefits and costs of land treatment in the Nepper Watershed in Iowa, and Tolley (ref. 28) illustrates the evaluation of both structural and land treatment works in the Mud Creek Watershed in North Carolina.

James (refs. 13-15) used the Stanford Watershed Model to evaluate changes in flood peaks due to urban development. By varying constants describing the physical conditions of a catchment, the effects of urban development and channel improvements were estimated. The results were used in an economic evaluation to find the minimum cost combination of structural and non-structural measures for flood control in a 43.8 square mile catchment in California.

By contrast with the relative abundance of benefit-cost examples of flood mitigation projects, there are very few examples dealing with drainage works. The only information readily available was related to increased land productivity as a result of subsurface drainage, rather than any catchment benefits or flood mitigation benefits. The example by Menz (ref. 29) illustrates the benefits from increased crop production due to farm drainage. Some data on the costs of dredging and maintaining open channels are given by Roehl (ref. 30).

11.4 WATER YIELD

A few studies have been directed towards economic evaluation of land treatment measures which affect water yield. In 1963, Hill (ref. 32) analysed the costs and benefits of obtaining additional water by converting deep rooted brush cover on a catchment to grass. He describes the work and costs involved in removing brush from a canyon bottom by logging, chemical treatment of stumps, and aerial spraying. The cost of the additional water yield which was expected by this method was higher than the cost of water from other sources.

Tabler (ref. 33) analysed the economics of inducing snow accumulation by snow fences in alpine areas. Using previously established data on the extra amounts of snow accumulation that could be expected from the fences, and assumed costs per mile of fence, Tabler shows that a relationship can be established giving the optimum amount of fencing to be constructed for any given value per acre foot of water.

Roberts and Wennergren (ref. 31) made an economic evaluation of the benefits obtained from stockwater development. The benefits listed in this study included increases in carrying capacity, increases in stock value, and reductions in farm management costs. They are examples of the benefits which can form part of catchment management projects related to water yield.

11.5 WATER QUALITY MANAGEMENT

Very few of the economic studies of water quality management which have been made are related to pollution from rural land use. However, this seems of little importance. The basic principles of economic evaluation of pollution management can be applied to the influence of rural land use on water quality using exactly the same methods currently used for managing urban and industrial pollution problems. The following review of studies and methods illustrates the current state of the art.

A treatise on the economics of regional water quality management with particular emphasis on the Ruhr Valley in Europe has been prepared by Kneese (ref. 34). In the U.S.A., a major study of the economics of water quality management in the Delaware Estuary, the Delaware Estuary Comprehensive Study of the U.S. Public Health Service, has been reported in a number of papers.

This latter study involves many waste dischargers, tidal influences in the estuary, and other complexities. The basic physical model of the behaviour of the pollutants in the river and estuary system was prepared by Thomann (see ref. 37). Sobel (ref. 36) describes the evaluation of costs associated with alternative quality goals, and Johnson (ref. 38) describes a study of effluent charges for allocating costs. The benefit-cost criterion used in the study was optimised using a linear programming model as described by Sobel (ref. 35). An extension of the original study was made by Graves, Hatfield and Whinston (ref. 39) to introduce by-pass piping as an additional factor into the analysis.

Liebman and Lynn (ref. 43) used dynamic programming to minimise the cost of providing waste treatment to meet specified dissolved oxygen concentrations in the Willamette River in Oregon. Revelle, Loucks and Lynn (ref. 40) used linear programming as an alternative method of analysis for the same problem. Results from the two methods were substantially the same.

Bramhall and Mills (ref. 44) have made an economic comparison of the costs of achieving given stream qualities by various combinations of low flow augmentation by dams and waste treatment. These authors discuss three alternative ways for the regulation by governments of the amounts of wastes entering streams - by regulation and enforcement; by payments such as tax concessions; and by charges or fees on processes or enterprises that generate large amounts of pollution.

Recreational benefits in water resource management are now of considerable concern in the U.S.A. Stevens (refs. 45-47) gives a good review of the evaluation of recreational benefits which can be obtained from pollution control. Parker and Crutchfield (ref. 48) report on the long-term social costs resulting from pollution of water resources, and conclude that these are substantially important, contrary to the lack of importance that long-term benefits usually contribute to the total present worth of projects.

The management of salt is of particular concern to Australia but there is little published information on the economic evaluation of this aspect of catchment management. In the U.S.A., Pinock (ref. 51) has developed an economic model for assessing the impact of declining water quality on the agricultural production of irrigated areas. The major review of salt in the River Murray, currently (1969) being prepared for the River Murray Commission, includes an evaluation of benefits and costs of alternative proposals for managing salt in the river system.

11.6 SOIL CONSERVATION

The principal economic benefit obtained from soil conservation works and practices is from increased production of the land. Standard texts such as those by Bunce (ref. 53) and Held and Clawson (ref. 54) give a good coverage of objectives and the methods of evaluation used. These benefits usually occur in any catchment management programme which incorporates soil conservation works, and there is no clear separation between the hydrologic benefits obtained and the normal benefits from increased production.

Soil conservation works consist of structural works, such as dams, contour banks and the like, and non-structural measures such as improved agronomic and cultivation practices, control of grazing, etc. The effects of flood retarding dams in reducing flood damages are well documented, and there are many examples of evaluating flood mitigation benefits and costs in the U.S. literature. These have already been reviewed in Section 2.2 and are not repeated here. The principal benefits obtained from the non-structural works are from reductions in erosion damages at the site of the works, and reduction of damages from deposition of sediments further downstream.

Knutson (ref. 57) has set out the rules-of-thumb used by the U.S. Soil Conservation Service for quick evaluation of whether a catchment scheme is worthy of detailed study. These criteria, which follow, clearly illustrate the types of schemes involved in their catchment management work and the major factors of the economic evaluation.

Water Control Projects:

1. 3% or more of the watershed in a flood plain at least 800 feet wide.

2. Presence of a flood plain with frequent damaging floods.

3. No serious soil limitations that would prevent floodplain development if flood hazard was removed.

Gully Control Projects:

1. Productive cropland destroyed or depreciated by gully erosion at a rate of 4% to 6% of total area in a 50 year period (0.1% per year).

2. More than one "sizeable" structure per 1000 acres needed to control the problem.

3. The prevention of voiding or depreciating of about one acre of cropland per year will justify a "sizeable" structure.

4. The extent and severity of gully erosion problems are related to the soil association area in which they occur.

Drainage Projects:

1. If a drainage problem exists and the size and complexity of the problem warrants group action, a project is almost certain to be feasible.

The starting point for evaluation of works which reduce sediment production is generally the "Universal Soil Loss Equation" devised by Wischmeier and others (refs. 62, 63) in the National Runoff and Soil Loss Data Laboratory of the U.S.D.A. at Purdue, or similar equations for predicting soil loss (e.g. see refs. 64, 65, 66). It may be noted that these equations and methods refer only to sheet erosion and do not include gully erosion as a source of sediment. A current project at the University of Queensland, financed by the Water Research Foundation of Australia, has the objective of deriving seasonal erosion indices from rainfall data using the rainfall index of Wischmeier's soil loss equation.

The next stage is the relationship between amount of soil loss and reduction in crop yield. Swanson and Harshbarger (ref. 67) illustrate a current approach to this relationship. Maccallum of the N.S.W. Department of Agriculture has also established a similar relationship (ref. 68) for a situation in the U.S.A.

The soil loss equation and crop yield relationship provide a basis for economic evaluation of soil conservation programmes. A colloquium on Soil Conservation held at the University of New England on 23-28 May, 1967 included several papers which dealt with the subject (refs. 70-74). Other papers cited in the references (refs. 77-86) deal with the economics of soil conservation in Australia.

The Task Committee for Preparation of a Manual on Sedimentation, of the American Society of Civil Engineers, has reported (ref. 75) on the economic aspects of sediment including damages from erosion of the land and damages from deposition of sediment. The report cites an estimate in 1948 by Brown (ref. 76) that the total annual damage from sediment deposition in the U.S.A. was approximately $174,000,000 compared with total annual flood damages of $100,657,000. The estimate was made up as follows:

1. Damage to agricultural land resources from overwash of infertile material, impairment of natural drainage, swamping due to channel aggradation, associated flood plain scour, and bank erosion - $50,000,000.

2. Damage from sedimentation in storage reservoirs used for power, water supply, irrigation, flood control, navigation, recreation and multiple use - $50,000,000.

3. Cost of maintenance or progressive impairment of the capital value of drainage works - $17,000,000.

4. Cost of maintenance of irrigation enterprises - $10,000,000.

5. Cost of maintenance of harbours and navigable channels as a result of sedimentation caused by erosion on the catchment and stream banks but excluding sedimentation caused by tidal currents in harbours - $12,000,000.

6. Cost of water purification as a result of excess turbidity - $5,000,000.

7. Sedimentation damages wholly or partly included in flood damage estimates including crop losses due to deposits of sediment on plants, costs of cleaning sediments from streets, etc., increased flood heights due to channel aggradation - $20,000,000.

8. Other damages not yet evaluated separately including the increased maintenance costs of highways, railways, oil and gas pipe lines, communication lines, damage to power turbines, damage to the fish and oyster industry, damage to wildlife, damage to recreation and impairment of public health - $11,000,000.

11.7 FORESTS

Most economic studies of forest management in Australia have been related to the evaluation of timber production and only little attention has been given to the economics of catchment management. Leslie (ref. 87) gives a general description of the benefit-cost evaluation procedures used in plantation development programmes, and in another paper (ref. 88) gives an example of evaluation which includes values of benefits for watershed and recreation purposes. McGrath (ref. 89) also gives data for catchment benefits in another example. Gatenby (ref. 91) discusses catchment management aspects of forests in New South Wales and briefly mentions benefit-cost evaluation. He cites an F.A.O. report by Francois (ref. 92).

Black (ref. 95) has made an economic analysis of the relation between timber and water production on the Frazer River catchment which provides water for Denver, Colorado. Flora (ref. 97) discusses the economic impact of diverting forest land to public purposes that do not include timber production. Zivnuska (ref. 94) discusses the benefits and costs of controlled burning in catchment areas as an alternative to the less frequent but more damaging wildfires. This paper deals essentially with the chaparral covered catchments of California.

A symposium dealing with the managing of forested municipal water supply catchments was held at the University of Massachusetts in November, 1965 (see ref. 16). Three papers dealing with the economic evaluation of the catchments are included in the proceedings. Another symposium held in March, 1966 at the Oregon State University on the practical aspects of watershed management (ref. 96) includes several papers on the economic aspects of multiple-use management.

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CHAPTER 12

SUMMARY AND RECOMMENDATIONS

The previous chapters and parts of this report have drawn together the available information on the various aspects of catchment management. The annotated bibliography should be of value to those seeking a ready source of information on the subject, and there is little need to summarise this material beyond the end-of-chapter summaries already given.

There is an additional objective of the project beyond this, and that is to identify the significant gaps in current knowledge and to propose suitable approaches for making good these gaps. In order to make such proposals, it is necessary to consider the gaps in current knowledge in conjunction with current research activities and work in progress. In the following sections, consideration has been given to current activities, and where appropriate, some proposals have been made for better utilization of existing data rather than initiation of new studies.

12.1 WATER YIELD

12.1.1 Summary of Effects

One of the major changes that has occurred in Australia in 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 resulted. Where deep rooting trees have been replaced by shallow rooting grasses, an increase in the total amount of runoff from the catchment usually results. In areas of Western Australia, South Australia, and Victoria, the change from trees to grass has resulted in the raising of saline groundwaters at the foot of slopes and in the bottoms of valleys with subsequent salting of large areas of ground as water evaporates and the salt is accumulated on the surface. Raising of groundwater levels without any problems of salting has been recorded in the Callide Valley of Queensland.

. Changes in runoff and/or groundwater recharge appear to be mainly due to effects on the evapotranspiration loss of the vegetation on the catchment. From the evidence available, three major influences on runoff and groundwater recharge seem to be significant:

(i) differences in incoming energy due to variations in slope and aspect over a catchment or between catchments.

(ii) differences in the rooting depths of vegetation which create different moisture deficiencies as the catchment dries out.

(iii) cultivation and cropping practices such as fallow which greatly reduce evapotranspiration loss for significant amounts of the year.

(iv) changes in land use which affect interception capacity, infiltration, or surface depression storage, do not show any consistent effect on water yield.

There is considerable evidence to show that conversion from trees to grass has resulted in increased surface runoff or groundwater recharge in a wide range of locations throughout the world. From the information available, it is possible to conclude that the cause is primarily the different rooting depths of the two forms of cover. The deeper rooting trees are able to extract more moisture from the soil than grass when climatic conditions permit, and so abstract more rain from following storms for soil moisture replenishment.

Because the effect is dependant upon climatic pattern, the amount of the increase in runoff or groundwater recharge due to clearing is not the same in all cases, but annual differences of 3 to 4 inches could be about the order of magnitude. No general prediction models have been developed for simulating the differences in water balance between trees and grass, but there seems no reason why current mathematical catchment models could not be used for this purpose.

In Australia, the difference in water yield between trees and grass as catchment covers, is most evident and of most concern as a difference in groundwater recharge rather than a difference in surface runoff. While the change from trees to grass can be treated as a single hydrological problem without separation into groundwater and runoff aspects, it is the influences on groundwater that have been of most practical concern, and this extends to the problem of salinity associated with clearing.

There are three reasons for this. First, increases in groundwater recharge accumulate and even small changes show up over a period of time. Second, changes in available water are small and changes in groundwater recharge have raised shallow saline groundwaters and have caused obvious and serious salting problems which are much more significant than the changes in recharge which produced them.

There is no evidence that soil conservation works and practices on a large scale are likely to reduce runoff to a significant extent. Farm dams have an obvious effect in abstracting runoff for use, but terraces and contour banks do not appear to reduce water yield in any systematic way. Some practices which affect evapotranspiration loss may affect water yield. The grassing or afforestation of bare areas seem likely to produce the most reduction in yield. Practices such as fallow which reduce evapotranspiration loss are likely to increase water yield.

Analysis of the differences in yield due to changes in land use are more complicated on large catchments than on small areas due to variation in hydrological behaviour over the catchment, to interflow and transmission losses, and to greater complexity in the groundwater patterns. Most research results are from experiments on small areas. It would be rash to extrapolate such data directly to large areas.

In a wide area extending from Western Australia to Victoria, the increased recharge of groundwater following clearing has resulted in raising of shallow saline groundwaters to the surface of the ground at the foot of slopes and in the bottoms of valleys. The salt, which accumulates at the surface as the water evaporates, has resulted in the gross deterioration of large areas of land, amounting to about 400,000 acres in Western Australia, 30,000 acres in South Australia, and over 10,000 acres in Victoria. This problem is dealt with in section 5 "Salinity" of this part of the report.

Since the Australian Forestry Council agreed to an accelerated programme of planting exotic pine species to make Australia self-sufficient in softwoods, some attention has been given to the hydrologic effects of replacing native eucalypt forest with radiata pine. An experiment has been in progress at Lidsdale in New South Wales since 1963, and early results show no substantial difference in water yield from catchments covered with eucalypt and pinus radiata. Overseas studies in the U.S.A. and South Africa support the conclusion that there is no significant difference in yield between hardwood and softwood species other than can be attributed to differences in root depth.

Argument has been raised concerning the Melbourne water supply catchments that replacement of mature forest with young growing trees will decrease water yield. However, this proposition has no support whatsoever from the evidence available from overseas studies.

12.1.2 Work in Progress

There is a considerable amount of experimental work in progress related to the effects on water yield of soil conservation works, forestry practices, and differences in catchment cover.

Soil conservation studies have been made on different areas ranging in size from fractional-acre plots to catchments up to about 200 acres. In brief, the experiments which have been or are being undertaken in Australia are:

Queensland:	The Department of Primary Industry operates three experimental catchments, 30-40 acres in size at the Brigalow Research Station at Theodore.
New South Wales:	The Soil Conservation Service has an experimental catchment at the Wagga Research Station and 1/30th acre plots at Wellington Research Station. Yield data is also available from a flood study by the Department of Conservation at Pokolbin. CSIRO's Division of Plant Industry has established four 20-acre experimental catchments in the Shoalhaven catchment area.
Victoria:	The Soil Conservation Authority has a group of seven catchments at Parwan.
South Australia:	The Department of Agriculture has established paired catchments at Moculto.
Western Australia:	The Department of Agriculture has established a 60-acre catchment at Moora, and two x 48-acre catchments at Corrigin.
Northern Territory:	The Northern Territory Administration has established the Walsh Creek project to study the effects of soil conservation works in a semi-arid environment.

The influence of fallow in controlling soil moisture depletion is already recognised, and studies have been undertaken in several states; in Queensland by the Department of Primary Industry on the Darling Downs; in Victoria by the Agricultural Engineering Department of the University of Melbourne at the Mt. Derrimut Field Station; and in South Australia by the Department of Agriculture and by CSIRO Division of Soils.

There are forestry studies in progress in Queensland, New South Wales, Victoria, and the Australian Capital Territory.

In Queensland, the Department of Forestry has established two small experimental catchments, 50 and 80 acres, at Atherton to study the hydrologic effects of conversion from tropical rainforest to tropical pastures. Another comparative study of the water use of Hoop Pine plantation, rainforest, and pasture on the Atherton tableland is being established.

In New South Wales, the Forestry Commission and the University of New South Wales are cooperating in a study of the comparative water yields of eucalypt and pinus radiata forests at the Lidsdale State Forest near Lithgow. Eleven catchments ranging in size from 10 to 240 acres have been instrumented since 1963.

In Victoria, the Soil Conservation Authority on behalf of the Land Utilization Advisory Council has established five experimental catchments, 10 to 65 acres, in State Forest near Daylesford for general study, and two catchments, 250 and 360 acres, near Myrtleford to study the effect of conversion from eucalypt to Pinus speciies. The Melbourne and Metropolitan Board of Works has collected data on water yields from three forested catchments at Coranderrk since 1956 to determine the effects of forest cover and forest management practices on yield, and is currently establishing another large group of experimental catchments.

In the A.C.T., a group of forested experimental catchments is operated by the Watershed Management Section of the Forestry and Timber Bureau in the Cotter River catchment near Canberra.

12.1.3 Recommendations

Two points can be made about the current experimental catchment work. First, there is very little interchange of data or analysis of data away from the point of collection. While a few instances may be cited of data being made available for university research, the general pattern is one of isolated experimentation, predominantly by Government departments, with little use of the data being made other than by the officers immediately concerned with the experiments.

The second point is that, to date, much more attention has been given to data collection than to data analysis. Little use has been made of advanced methods of analysis for analysis of the data already available. It seems necessary, for any progress in developing methods for routine assessment of the effects of land use on water yield, that computer simulation of catchment water balances, usually termed "mathematical catchment models", should be used for analysis of the data from experimental catchments.

However, the Government departments which are carrying out the experimental catchment work are still far from orientated towards these methods of analysis. The prospects of the methods of analysis being improved within the data collecting authorities is not good, and when this is combined with the very limited circulation of data away from the point of collection, there seem to be poor prospects for any rapid production of useable results from this field of research.

At the present time, the Snowy Mountains Authority is collating existing data from small catchments less than ten square miles in area, as part of the Australian Water Resources Council's research project 68/1 - Hydrology of Small Rural Catchments. In addition, data from the system of representative basins, which range from 10 to 100 square miles in area, will be analysed by the mathematical catchment model now being developed by the Land Research Division of C.S.I.R.O. There is no such attention being given specifically to the catchments on which land use experiments are being undertaken, or to the experimental techniques being used.

One method of fostering the interchange of data and narrowing the gap between data collection and analysis, would be to arrange for periodical meetings between representatives of the agencies which are operating experimental catchments and the analysis in Universities, C.S.I.R.O., and other agencies which are most concerned with the use of mathematical catchment models. The meetings could be arranged as seminars with attendance limited to those directly involved, or as an ad-hoc sub-committee of the A.W.R.C. Water Research and Education Steering Committee. Another method would be to sponsor a research project similar to 68/1 - Hydrology of Small Rural Catchments - to collate and analyse the data already available from land-use experiments. This assumes the willingness of the data-collecting authorities to cooperate, a matter to be first clarified.

In general, it is recommended that -

"Consideration be given to methods of improving the utilization of data from experiments which have already been established on catchments in Australia for the purpose of evaluating the hydrologic effects of land use and land management."

One important aspect of this field of research is how to extrapolate the results from small experimental catchments to large areas. This is a fundamental part of the utilization of any results which may be obtained; yet there is virtually no research effort being applied to the problem in Australia and very little in overseas countries. The problem and current knowledge have been reviewed in Chapter 3 of Part 1. This topic warrants particular attention to stimulate research and to make authorities aware of the problem.

It is therefore recommended that -

"Consideration be given to the need to stimulate research into the problems of extrapolating results from small experimental catchments to large areas."

No attempt has been made in this project to survey the instrumentation of experimental catchments or assess the quality of data available. However, one point is clear-most experiments collect only rainfall, runoff, evaporation and some other meteorological data. There is a strong trend to the collection of soil moisture data, and in one case ground water levels are regularly monitored. Generally, the data collected do not go beyond rainfall, runoff and some meteorological information.

The type of data that is available strongly influences the type of analysis which can be made. For example, developments to date in mathematical catchment models have been limited by the date available, i.e. rainfall input and runoff and evaporation output. Models tend to be "black-box" mechanisms which give good relationships between input and output, but which bear little relationship to the actual physical processes occurring on a catchment. This is clearly evident by the failures which have been experienced in efforts to relate model parameters to catchment characteristics.

If new methods of analysis are to be fostered, then new types of data must be collected, but it is difficult to specify what additional information should be collected. Indeed, the arbitrary decision in advance to collect specific data then restricts future analyses to use of those data. There is a need for a few catchments to be established throughout Australia on which a wide range of data is collected at a very high standard of measurement, and the data widely circulated to encourage new methods of analysis. This would provide opportunities for a wide range of new developments to be formulated and tested.

I suggest that one such "centre-of excellence" in each state would be an appropriate initial objective; that water quality data should be collected in addition to data for water yield and floods; and that utmost importance be attached to regular processing and publishing of data.

The need to advance in methods of hydrologic analysis has been recently emphasised by the strong interest in the Conference on Water Research held in Canberra in January, 1970. The need for a few centres where very high quality data are collected and made freely available for analysis seems to be as strong as the need for better utilization of data from existing catchment experiments.

It is therefore recommended that -

"Consideration be given to the need for collecting some very high quality hydrologic data at a few select locations throughout Australia to provide opportunities for development of new methods of analysis."

Where runoff or groundwater recharge has been increased by conversion of a catchment cover from trees to grass, the critical drought periods that occurred in the streamflow record prior to clearing may no longer be representative of the future flow pattern. Where the statistical characteristics of a streamflow record are used to generate synthetic flow sequences, the changes produced by clearing could significantly influence the low flow sequences which are all important in reservoir design.

In the Callide Valley in Queensland, a critical drought period in the streamflow record occurred early this century before the valley was substantially cleared of trees. This critical period is the present basis for restricting further irrigation development in the valley. However, there may be additional surface runoff and groundwater recharge resulting from the conversion of plant cover from trees to grass which would permit additional development if properly assessed.

Studies in South Australia have already shown that differences in water use between trees and grass substantially alter the amount of groundwater recharge and the amount of groundwater available for development. In the area studied, there is virtually no surface runoff and the groundwater is the principal water resource. There have been no studies made of how the changes in surface flow or groundwater recharge produced by change in land use can affect reservoir design or estimates of the reliable yield of a catchment or aquifer.

This is a problem of wide ramifications. Land use changes such as clearing have most effect on low flows, and these flows are most significant in determining the amount of development which can be sustained by the available water. Almost all methods of analysis of streamflow records depend on assumptions of homogeneity of the data. There is a need to know how much effect is introduced by a change in the low flow pattern such as would occur from the effects of clearing.

There is scope here for some order-of-magnitude estimates to be made of how important is change in the homogeneity of streamflow records resulting from change in land use. Current knowledge, as outlined in Parts I and II of this report could be used to give order-of-magnitude estimates of the results of changes, such as the clearing of trees from a catchment, and these estimates can serve to estimate the likely economic consequences of a change.

It is therefore <u>recommended</u> that -

"<u>Consideration be given to the need for a research project to study the order-of-magnitude of economic effects resulting from change in a catchment plant cover from trees to grass in a few select locations, such as the Callide Valley in Queensland, the Gambier Plain in South Australia, and the South-West coastal strip of Western Australia.</u>"

12.2 FLOODS

12.2.1 Summary of Effects

Overseas results show that land treatment measures have little potential for significantly reducing floods on large catchments.

In the small watershed programme of the U.S. Soil Conservation Service, flood detention dams, with a storage capacity equivalent to about 3½ inches of runoff from the catchment area controlled, are used as the primary flood mitigating measure. The reductions in flood peaks are greatest immediately downstream of the detention dams, and the effect diminishes with distance downstream. A number of studies have shown that dams on tributaries mitigate flooding in those tributaries but have little influence on floods in the main river channel. The next most important flood mitigation measure in U.S. programmes is channel improvement to reduce overbank flow.

Land treatment measures, particularly contour banks and terraces, can reduce the peaks of small floods on small catchments. However, there is insufficient information available to generalize results or produce a general prediction model. Generally, the reductions seem to be significant only where the flood results from short duration high-intensity rain with runoff volumes of 2 inches or less. For a storm runoff of 2 inches, reductions in flood peaks due to land treatment would be in the order of 5% to 15%. In Australia, most floods (even on small to medium catchments) are the result of cyclonic storms which produce large amounts of runoff, of the order of 5 to 10 inches. Land treatment measures may have a small effect on flood peaks from small catchments under these conditions, but virtually no influence on flood peaks in large catchments.

Bushfires can have a significant effect in increasing in runoff volumes, flood flows, and sediment yields. American data suggest that flood peaks may be doubled during the first year after a severe burn and that a period of 7 to 8 years is probably required to restore pre-burn conditions. The majority of results available for study are from California which has a bushfire problem similar to that in Australia.

There is opportunity for land management to influence the effects of bushfires by periodic control burning to prevent fuel accumulation and so reduce the severity of wild fires. Because the intensity of a control burn is very much less than that of a wild fire, the effect on plant cover is small, and any influences on runoff should take a much shorter time to disappear.

12.2.2 Work in Progress

An experiment to determine the effects of soil conservation works on flood peaks was established by the Department of Conservation of New South Wales at Pokolbin in the Hunter Valley several years ago. From the little evidence which is available, it appears that this is probably the best instrumented and maintained experiment of its type in Australia but very little has been published about the experiment and no results have been made public. It seems that the experiment has not shown any significant effect of soil conservation works on flood peaks to date but this comment should not be taken as conclusive. To the best of the writer's knowledge, this experiment is still continuing.

In Victoria, the Soil Conservation Authority has established Limpet level recorders at a number of locations throughout Victoria to determine possible variations in peak flow from catchments under agricultural production. The experiments conducted at Parwan by the Soil Conservation Authority, mentioned in the previous section on water yield, have also been used to study the effects of land management on rates of runoff.

In Western Australia, the Soil Conservation Service of the Department of Agriculture is studying the effect of soil conservation earthworks on the runoff hydrograph at the Berkshire Valley experimental catchment, Moora.

The effect of bushfires on runoff flood flows and sediment yield is being studied in the Snowy Mountains area, in Queensland, and in Victoria. Following a severe bushfire in the Upper Tumut Valley in March 1965, a study of its effect on sediment yields, catchment runoff and floods was commenced by the Snowy Mountains Hydro-Electric Authority. The Queensland Department of Forestry and the Forests Commission of Victoria are both using small plots (about 60-75 square feet) to study the effects of control burning practices, but these are more related to sediment and water yield than to floods.

The effect of drainage works on flood flows has been studied at the University of Queensland, Department of Civil Engineering. An hydraulic model of the stormwater drainage of reclaimed coastal swamps was used to determine the increase in flood levels in an adjoining river due to the removal of the flood storage capacity of reclaimed areas in the Kawana Island land development.

12.2.3 Recommendations

Much of the problem of determining the influence of land use on floods lies in the lack of knowledge about the build-up of the flood hydrograph across the land surface and in the channel system of a catchment. Most models of the flood hydrograph, e.g. unit hydrographs or runoff routing models, are based on rather arbitrary relationships between rainfall and runoff. There is little basis for relating change in land use to change in unit hydrograph or other model parameters.

On larger catchments, storage effects in the main river channel tend to dominate, and it is possible to evaluate the effects of clearing, straightening, etc. of the river channel by standard methods of hydraulic analysis. The influence of flood detention dams can also be evaluated by standard routing techniques.

On smaller catchments, the Rational Method is more commonly used to estimate flood flows, using either a coefficient of runoff or a loss rate. The recommended coefficients and loss rates contained in "Australian Rainfall and Runoff" do not seem to be realistic; in particular, the effects of forests and other vegetation on flood peaks seems exaggerated for the conditions in Australia where cyclonic storms are most prevalent.

In view of the wide use which is made of "Australian Rainfall and Runoff' for estimating flood flows, there is a need for the best available information to be used in the recommended procedures. There is considerable information now available in the published results of experiments which might be of use, if evaluated in detail, in improving the current recommendations.

It is therefore recommended that -

"Attention be given to the available information on effects of land management on flood flows in any examination of possible revision of "Australian Rainfall and Runoff".

There is considerable concern among water supply authorities about the effects of bushfires on catchment areas. Some authorities have knowledge of and experience with control burning, but there is an obvious need for a wider dissemination of knowledge to many of the authorities. The Water Resources Council or the University of New South Wales could assist by arranging for a symposium on the control of fire on water supply catchments, possibly in conjunction with a Rural Fires Conference of the Forestry and Timber Bureau, or with a biennial meeting of the water supply and sewerage authorities.

It is recommended that -

"Consideration be given to sponsoring a symposium on the control of fire on water supply catchments."

12.3 WATER QUALITY

12.3.1 Summary of Effects

Rural land use affects the quality of available water in Australia by increasing the level of turbidity and sediment, by bacteriological contamination from animal wastes, and by the leaching of pesticide residues. The effects of land use on salinity in water is described in a separate section.

Turbidity in water supplies can be substantially increased by clearing of land in the catchment, by construction activities on or near water-courses, by forestry operations such as logging, and by cultivation. The problem is more widespread in catchments providing town and city water supplies than is generally realized. The example of Canberra's water supply is probably the best documented; however, many other similar cases have occurred.

Bacteriological contamination from animal wastes has not produced widespread problems in Australia but this is undoubtedly because of the many controls which exist in public health and catchment management legislation. Pig farming is given particular attention in most regulations governing use of catchment lands, and the disposal of carcasses of dead animals is also controlled. In the U.S.A., problems are occurring because of high concentrations of animals on small areas in large-scale "factory farming". In cool climates where much runoff occurs from saturated ground each winter, animal wastes are not absorbed into the soil and tend to contaminate surface water supplies. Neither of these two problems is widespread in Australia.

The use of artificial fertilizers on agricultural lands is increasing rapidly and, because applications are never even or exact, the leaching of nutrients, particularly nitrate and phosphate, into water supplies is increasing. Infants and young animals are poisoned by excessive amounts of nitrate, but this does not appear to have happened in Australia. The more practical problem occurs where the nutrients accelerate the growth of algae and water weeds. Blooms of algae can deplete the oxygen in water and die, leaving an unpleasant taste and discoloration in the water. Clogging of filters, pumps and pipelines can occur. Problems with algal blooms have already occurred in most states.

12.3.2 Work in Progress

Particular mention must be made of the Senate Committee on Water Pollution which collected evidence throughout Australia during 1969 and which is expected to report to the Federal Parliament in 1970. Although the activities of this Committee do not fall within the general field of research, the collection of evidence will constitute the most comprehensive review ever compiled of problems and current activities related to water pollution in this country. The effects of rural land use on water quality are included in addition to the effects of urban and industrial areas.

Most water supply authorities and public health authorities are active in both routine monitoring of water quality and some investigations of causes and control of pollution. However, problems of water quality resulting from rural land use are closely mixed with urban and industrial pollution problems. Water pollution is too big a topic for review in this project.

One particular activity which merits attention is the survey of water quality in some 50 rivers in Queensland by the Local Government Department. Sources of pollution, both rural and urban, are being identified, and data for later analysis are being collected. The Department intends to develop mathematical models for analysis and prediction of the behaviour of pollutants in the river systems.

A mature forest cover is generally accepted as the best protection for a water supply catchment, but clearing and cultivation for establishment of plantation forests, construction of access roads, and logging activities are, by nature, not conducive to maintaining high water quality. Forestry and land utilization authorities are well aware of this source of conflict in multi-purpose use of catchment lands and several studies are in progress. In Queensland, the Department of Forestry has studied the effects of commercial logging in Freshwater Creek basin, west of Cairns. In Victoria, the Soil Conservation Authority on behalf of the Land Utilization Advisory Council is initiating collection of water quality data on some experimental catchments. In New South Wales, the Forestry Commission has proposed a detailed research programme to study how management practices affect water quality.

Pesticide residues in agricultural products intended for export have already received attention by the Australian Agricultural Council, which has established a Sub-Committee to study the problem. There would be benefit from close cooperation between the Water Resources Council and the Agricultural Council concerning pesticide residues in water supplies.

12.3.3 Recommendations

Because the scope of the present project has been very broad, encompassing both water yield and floods in addition to aspects of water quality, there is still scope for more detailed study of individual aspects. This applies particularly to water pollution from rural land use. In general, there is a need for more detailed reviews of bacteriological contamination from animal wastes, of excess nutrients, and of pesticides, before any recommendations for further research could be formulated. Two detailed recommendations can be given here, one concerning utilization of existing turbidity data and the other related to development of mathematical models for study of water quality.

Turbidity is a problem in many water supplies in Australia; yet relatively little is known about the types of soil or patterns of disturbance which are most troublesome, or how construction, forestry, or other activities can be undertaken in or near watercourses with minimum effect. Surprisingly, very little research is being directed towards the problem.

There appear to be large amounts of data on turbidity levels in streams which have been collected by water supply authorities in routine monitoring of their supply. There is a major opportunity for research of a substantial practical problem, without involving expensive or lengthy data collection, by collating and analysing the existing collections of data.

Research needs related to turbidity are complex and involve aspects of soil type, climatic patterns of high-intensity rain, cultivation and management practices in forestry and agriculture which initiate disturbances, and the persistence of turbidity in water downstream from a disturbance. Without attempting to specify detailed aspects or break up the problem in any way, a broad recommendation for more research in this field and for better use of existing data can be given.

It is therefore recommended that -

" Consideration be given to sponsoring research into the causes of turbidity in town and city water supplies and methods of control of the problem."

In the U.S.A. mathematical models of the behaviour of pollutants in rivers and estuaries have been developed for both conservative and non-conservative pollutants to deal with such problems as salt, nutrients, pesticides, bacteriological contamination from animal wastes, and even thermal pollution. The models are used in conjunction with a hydrological model of the water system to predict the movement, dispersion, decay, and ultimate disposal of pollutants in the same way that the mathematical catchment models deal with the water balance of catchments.

In Australia, very little use of water quality models have been made until recent time. In South Australia, there are current studies directed towards modelling of salt in the lower Murray River. In Queensland, the Department of Local Government has just commenced modelling the behaviour of a single pollutant in a simple river system as a step towards development of more realistic models. In Western Australia, CSIRO Division of Soils has already studied the movement of salt in small catchment systems following change in the hydrological regime resulting from clearing. Each of these studies could be described as exploratory.

There is good reason to stimulate the development of techniques in water quality analysis, particularly mathematical models of the behaviour of pollutants in rivers and estuaries. Water quality problems are increasing rapidly but, more important, public awareness of pollution is increasing at an even faster rate. The development of analytical techniques for understanding the behaviour of pollutants is a fundamental need for managing catchments where the land use is likely to produce water quality problems.

It is therefore recommended that -

"Consideration be given to stimulating the development and use of methods for analysing the behaviour of pollutants in rivers and catchments in Australia."

12.4 SALINITY

12.4.1 Introduction

In Australia, most groundwaters contain significant quantities of salts, and in many areas the salinity is very high. Problems occur when the activities of man result in raising the watertable close enough to the surface of the ground for evaporation to take place. Salt then accumulates as the water is lost and salinization of the land results.

There are two distinct aspects of this problem in Australia, one related to large scale irrigation development around the Murray River, and the other related to upset in the hydrologic cycle following replacement of the trees on a catchment with grass.

12.4.2 Murray River Irrigation

Salinity problems in the Murray River have been described in Chapter 6 of Part I of this report, and in the main they arise as a result of overwatering in the irrigated areas of the Riverine Plain. Water from the upland catchment of the Murray is of good quality, probably better than normally available for large scale irrigation in overseas countries.

However, the Riverine Plain is characterised by shallow groundwaters, most of which are highly saline. Natural drainage is poor. Overwatering and channel seepage losses have raised the watertables producing water-logging and salinization problems, and increasing the salt load entering the river. When combined with the reduction in flow by the use of water for irrigation, the result is that the quality of the river water is seriously degraded. Salinity of Murray waters increases continuously from Hume reservoir to the sea.

A major report on salinity in the river system has been prepared for the River Murray Commission by Gutteridge, Haskins and Davey, consulting engineers. The report is lengthy and comprehensive and covers the physical situation of climate, soils and geology in addition to the history of development, institutional arrangements for control of the river, and much other relevant material.

In this present review of catchment management, the problem of Murray River salinity is an important item. During the project, it became clear from discussions with members of the Advisory Panel on Effects of Land Management on Runoff and members of other A.W.R.C. committees, that consideration of the topic was desirable. However, the magnitude of the River Murray Commission investigation raised a problem.

The objectives which were intended for the irrigation aspects of this review of catchment management will be substantially met by the report to the River Murray Commission. The major problems will be identified and gaps in current knowledge identified. In the limited time available for the A.W.R.C. study of catchment management, it was impossible to approach the magnitude of the Murray River investigation, and there seemed little value in attempting to duplicate any major part of the work. It is understood that the report will contain recommendations for further research and investigation to be undertaken, ranging from fundamental studies to the need for more data to be collected.

It is therefore recommended that -

"Consideration be given to the recommendations for research related to salinity problems associated with irrigation development as outlined in the consultants' report to the River Murray Commission."

12.4.3 Salinity Following Clearing

One of the more evident changes in the hydrologic cycle produced by change in land use is the difference in water use between trees and grass. The deeper-rooting trees generally are able to extract a greater amount of soil moisture than the shallower rooting grasses. Where the climate is such that evapotranspiration exceeds rainfall for a significant amount of the year, the trees can create a greater soil moisture deficiency than the grass, and in following storms when the soil moisture is replenished, there is more surface runoff or groundwater recharge from grassed areas than from areas of trees.

The increased groundwater recharge which occurs when native forest is cleared for agricultural development can result in raised watertables, similar to the result of overwatering with irrigation. Where the groundwater is both shallow and saline, the increased recharge can raise the watertable to or close to the surface and the accumulation of salt as water evaporates can result in salinization of the land.

This effect of dry-land salting following clearing is most evident in Western Australia where about 400,000 acres of land are affected. The problem also occurs in South Australia and Victoria where lesser areas are affected. The areas affected are generally in a rainfall of 15" to 25 inches per annum, and there are substantial areas of such land currently being cleared and developed. A description of the problem is given in Chapter 2 of Part I of this report.

Salinity resulting from clearing dates back to the beginning of this century but, to the present time, the techniques of analysis have not developed much beyond the indentification and description of the problem, its cause, and the several variations of confined and unconfined aquifers, fine textured and coarse textured soils, etc. In Western Australia, CSIRO Division of Soils has instrumented some catchments to monitor both the salt and water balances, but the problem appears to warrant an increase in the current effort.

The problem is complex involving both surface flows and groundwaters, and both water and salt movements, and it requires precise measurement of the differences in water use by the plant cover as trees are replaced by grass. An essential feature of any analysis of the problem will be the development of techniques for study of the salt balance of a whole catchment under relatively natural or undeveloped conditions.

To date, developments in the analysis of salt balances of whole catchments have been associated with the salinity problems of large scale irrigation, where large amounts of water and salt are involved, where the useage of water and concentrations of salt are known, and where the elements of the salt and water balances are relatively easily defined. The problem of salinity resulting from clearing requires a more fundamental knowledge of the movement of water and salt in natural catchments, and involves more exact and intensive data for any analysis.

Any detailed formulation of research proposals in this field would be best undertaken in cooperation with the authorities in Western Australia and Victoria who are currently involved in study of the problem. For the purposes of this report, attention is drawn to a problem of catchment mangement that already substantially affects both land and water resources and that is likely to increase with future increases in land development.

It is therefore recommended that -

"Consideration be given to fostering increased study of the salt and water balance of catchments in areas where salinization problems develop as a result of clearing."

12.5 LEGISLATION, ECONOMICS AND RELATED ASPECTS

12.5.1 Introduction

The social, political and economic aspects of catchment management have the widest ramifications of all parts of the subject. The need for sound information on which to base policies and assessments is the starting point from where the priorities for research into the physical aspects of the subject can begin. The problems at this level of the subject are usually impressive in size.

The conflicts of interest which can occur between the users of land in a catchment and the downstream users of water from the area are not unknown in Australia. The conflict between timber interests, wishing to utilise timber from Melbourne's water supply catchments, and the interests of the water consumers in Melbourne has been the subject of more than one enquiry at State Government level. Similar conflicts arise in the Newcastle water supply catchments and in other parts of Australia.

Problems of social priority arise in the issue of mining leases which encroach on or encompass water supply catchments. Long standing practices of agricultural management in the Snowy Mountains area, involving grazing and pasture burning of alpine lands, had to be changed with the construction of the $800 million Hydro-Electric Scheme. Demands for recreational use of water supply catchments and a staggering rate of increase in public awareness of pollution and quality of the environment, are major problems for the immediate future.

The writer is well aware of the magnitude of the social, political and economic issues which are inherent in these problems. It would be easiest to ignore them as is most frequently done in assessments and reviews such as this project. It seems more responsible to make an effort towards delineation of where research effort might best be directed in this field as well as in the area of the physical sciences, in full knowledge of the sensitivities which exist around many of the current problems.

12.5.2 Legislation

In Chapter 10 of Part III of this report, a description was given of some of the legislation and regulations controlling land use in water supply catchments in Australia. Control over use of these areas is usually given to the water supply authority or to the state soil conservation authority in order to control pollution or erosion respectively.

The authority to control land use, in this context, is rarely singular and frequently there is overlapping legislation. It appears that there is far more power to control land use in catchments than is generally used, and the exact nature of control exercised in different parts of the country cannot be assessed merely by reading the acts and regulations which exist. In general, it seems that fairly wide powers have been established by legislation, and these are used as little as is necessary to meet localised problems. In most cases, the powers exercised are punitive (action taken when a complaint is received) rather than preventative (action taken to prevent problems from arising).

Because of the influence that mining activities can have on water quality, the legislation governing issue of mining leases is also relevant. In some instances in Australia, it seems that mining leases can be issued for areas in water supply catchments, even where this is against the wishes of the water supply authority. It has not been possible in the time available for this project to examine the relative priorities in such cases.

At the present time, the existing legislative control over land use in water supply catchments is far in front of the technical information which is available to guide the control. There is more legislation still being enacted to add to that already in existence, e.g. in New South Wales at the time of writing, legislation before the State Parliament includes a Water Pollution Bill, and a Land Utilization Bill, both relevant to the management of catchments. In Victoria, there is a Land Resources Bill in preparation which could substantially change the operation of the Land Utilization Advisory Council.

There are big differences in catchment management legislation among the States, and there is a need for a more detailed review than has been made in this project.

It is therefore recommended that -

"Consideration be given to the need for a detailed review of the legislation which deals with the control of land use in water supply catchments in Australia."

12.5.3 Utilization of Catchments

Present developments in the utilization of catchments in the south-east of the continent are sobering. There is a large area of catchment land in the Snowy Mountains regions which is now developed for power generation and for irrigation in the Murrumbidgee - Murray areas. Immediately north of the Snowy Mountain catchments, is the Cotter catchment which provides Canberra's water supply and which is now fully utilized for this purpose.

Future increases in supply for Canberra will be taken from the Queanbeyan - Molongolo catchments to the east of Canberra, and these abut onto the Shoalhaven catchment which is being developed for supplying water to Sydney. There is a great arc of catchments immediately north of the Shoalhaven, including the Warragamba catchment, Cataract, Cordeaux, Avon, and others, which are already fully utilized to provide water to Sydney and the Wollongong - Port Kembla region.

Recently, there has been controversy concerning the catchments to provide water supply to Melbourne. When the need for additonal areas was established in 1962, a proposal to divert water from the Big River in the catchment of the Goulburn River was not accepted by the Victorian Parliamentary Public Works Committee because "the water resources of the Big River and all other streams entering Eildon Reservoir are committed for water supply to the Goulburn Irrigation System." With the pending construction of Dartmouth reservoir at Mitta Mitta to increase the regulation of flow in the Murray River, almost all water from catchments along the Great Divide between Melbourne and Sydney will be committed for purposes which include municipal supply, irrigation development, or power generation. The amounts of uncommitted supplies or resources which can be further developed are diminishing fast.

There are other areas where the demands for water have reached the same stage of commitment, and where conflict between competing demands is beginning to emerge. The Moreton Bay region surrounding Brisbane is an example. Competing demands for water among the supply to Brisbane, supplies to smaller centres of population, irrigation development and others, have recently resulted in proposals for a Moreton Bay authority to plan and control future utilization of the available water in the whole area.

The need for improved techniques in management of these catchments is illustrated by the restrictions now imposed on the planting of pine trees in the Cotter catchment near Canberra, the restriction on burning and grazing in the high mountain catchments of the Snowy Mountains, the conflict between timber interests and the Melbourne and Metropolitan Board of Works concerning timber harvesting on the Melbourne catchments, and so on. The needs vary depending on the use to be made of waters from the catchments - different problems of catchment management occur depending on whether the water will be used for metropolitan supply, irrigation, or power generation.

Therefore, as a preliminary to defining the problems of catchment management in Australia, there is a need to set out the use to be made of the water from the major catchments and the purposes for which the catchments will be managed. Some effort has already been made in this direction. In Victoria, the Parliamentary Public Works Committee has already prepared reports on possible utilization of water from catchments of the Ovens, Broken, King, and Wannon Rivers, and Seven Creeks, as well as reports on the future water supply for Melbourne. In New South Wales, the Water Conservation and Irrigation Commission is preparing detailed reports on the water resources of the more than 30 river basins.

At this point in time, it seems opportune for these efforts to be supplemented by similar work in other states and for the commitments and demands for available water from major catchments to be collated on a national basis. When the Australian Water Resources Council was first established in 1962, one of its early achievements was the completion of a national assessment of the water resources of Australia which provided a basis for the subsequent programme of increased stream gauging activity and assessment of underground water resources. The current need is for a national assessment of the commitments and demands for available water and the accompanying requirements of catchment management.

At the conference on water research, held in Canberra in January 1970, there were suggestions for surveys to be made of land use throughout Australia for the purpose of assessing how change in land use might be affecting water resources. While these suggestions have obvious merit for the purpose of national planning, the task could be made much simpler by first defining the areas where demands for water and commitments of the available supplies are greatest.

It is therefore recommended that -

"Consideration be given to preparing a national assessment of the demands for water and commitments of the available supplies in the major river basins of Australia, and the accompanying requirements of catchment management."

12.5.4 Education

In the U.S.A., watershed management is an established discipline at a number of Universities, but the position is much different in Australia. Here, there is virtually no established teaching of catchment management at the present time. In the School of Civil Engineering at the University of New South Wales, where the teaching of hydrology has been most developed, catchment management is only a very minor item in the teaching of Public Health Engineering both at undergraduate and post-graduate levels. In the Department of Forestry at the Australian National University, there is only a little teaching of hydrology and of the role of forests, commensurable with the minor role of protection forests compared with the production forests in Australia.

Catchment management is generally practised as an art within the government organizations which have some legal control over or responsibility for catchment areas. The subject is apparently ignored by universities except for some isolated pieces of research by interested individuals. There is an absence of systematic teaching and of any programmes of research. There are current developments in the teaching of natural resource management, both at the University of New England and the Australian National University, but there is little indication at the present time that catchment will be adequately treated. The major difficulty seems to lie in the wide scope of the subject and the absence, prior to this report, of any substantial review of the problems which exist in this country.

No attempt was made in this project to review the educational aspects in detail, and it is recommended that some further consideration be given to this. Considering the important ramifications of existing catchment management legislation, it is surprising that no attempt has been made in the past to foster study of the subject. There would be merit in having a review of American courses made with any detailed review of relevant courses in Australia. Until such a review is made, there is little purpose in attempting to formulate detailed recommendations for further developing the teaching of the subject.

It is therefore recommended that -

"Consideration be given to the present absence of any systematic teaching of catchment management at university level in Australia."

12.6 SUMMARY OF RECOMMENDATIONS

The recommendations which have been made with explanation in the previous pages are summarised below. The recommendations are that priority of attention should be given to the following:-

(1) To methods of improving the utilization of data from experiments which have already been established on catchments in Australia for the purpose of evaluating the hydrologic effects of land use and land management.

(2) to the need to stimulate research into the problems of extrapolating results from small experimental catchments to large areas.

(3) to the need for collecting some very high quality hydrologic data at a few select locations throughout Australia to provide opportunities for development of new methods of analysis.

(4) to the need for a research project to study the order-of-magnitude of economic effects resulting from change in a catchment plant cover from trees to grass in a few select locations, such as the Callide Valley in Queensland, the Gambier Plain in South Australia, and the South-West coastal strip of Western Australia.

(5) to the available information on effects of land management on flood flows in any examination of possible revision of "Australian Rainfall and Runoff".

(6) to sponsoring a symposium on the control of fire on water supply catchments.

(7) to sponsoring research into the causes of turbidity in town and city water supplies and methods of control of the problem.

(8) to stimulating the development and use of methods for analysing the behaviour of pollutants in rivers and catchments in Australia.

(9) to the recommendations for research related to salinity problems associated with irrigation development as outlined in the consultants' report to the River Murray Commission.

(10) to fostering increased study of the salt and water balance of catchments in areas where salinization problems develop as a result of clearing.

(11) to the need for a detailed review of the legislation which deals with the control of land use in water supply catchments in Australia.

(12) to preparing a national assessment of the demands for water and commitments of the available supplies in the major river basins of Australia, and the accompanying requirements of catchment management.

(13) to the present absence of any systematic teaching of catchment management at university level in Australia.